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DESIGN GUIDELINES FOR DOUBLER PLATE REPAIRS OF SHIP STRUCTURES

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2005

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AUGUST 2005

DESIGN GUIDELINES FOR DOUBLER PLATE REPAIRS ON SHIP STRUCTURES

The use of doubler plates or 'doublers' for temporary ship repairs has become routine. It is the preferred method for temporary ships' structural repairs for plate corrosion due to its relative ease and low cost of installation over the more costly permanent welded plate insert repair. However, the ultimate goal of this project was to establish the design and limitations on the applications of doubler plate repairs for surface ships.

In this study a methodology for designing and using doubler plates was developed. The use of the methodology will provide quantitative technical rationale (criteria) for the design and limitations on the application of doubler plates as a repair fix for surface ships.

The guidelines were developed based on the responses received from several ship-owners, shipbuilders and classification societies during personal interviews and also using the results from finite element analysis performed to check buckling and fatigue strength of doubler plates. These guidelines were developed so that the damaged structure regains its original strength with the addition of the doubler plates and the repairs are considered permanent.

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16. Abstract

The use of doubler plates or 'doublers' has become routine for temporary ship repairs. It is the preferred method for ships' structural repairs for plate corrosion due to its relative ease and low cost of installation over the more costly permanent welded plate insert repair. A lack of performance data and engineering design guidance are the reasons that repairs with doublers are currently considered only temporary.

This project was created to develop a set of guidelines for designing and applying doubler plate repairs to ship structures. The guidelines were established using the following criteria: various stress analyses, buckling strength, primary stress assessment, corrosion types and rates, weld types, and doubler plate fatigue and fracture assessment. Studying and understanding doubler plate repair performance by comparison to that of the primary hull performance allows critical operational decisions to be made with greater ease and confidence. However, the ultimate goal of this project was to establish the design and limitations on the applications of doubler plate repairs for surface ships.

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To convert from	to	Function	Value
LENGTH			
inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet	centimeters^2 meters	multiply by	1.9665
inches^2 feet	centimeters^3	multiply by	196.6448
inches^3	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
inches^2 feet^2	centimeters^2 meters	divide by	1.6684
inches^2 feet^2	centimeters^4	multiply by	5993.73
inches^4	centimeters^4	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
pounds/inch^2	Newtons/meter^2 (Pascals)	multiply by	6894.757
kilo pounds/inch^2	mega Newtons/meter^2 (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tonnes	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo pound/inch^2 in√in)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3

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LIST OF ABBREVIATIONS AND SYMBOLS

a	Depth of pit
A	Area of the plate
B_L	Length of stiffened panel
B_W	Width of stiffened panel
B_t	Thickness of stiffened panel
c	Pit radius
c_{cr}	Critical pit radius
C	Corrosion rate
C_1,C_2	Corrosion constants
C_L	Length of corrosion feature on stiffened panel (if present)
C_p	Corrosion coefficient
C_t	Thickness of remaining ligament at the corrosion feature
C_W	Width of corrosion feature on stiffened panel (if present)
d,d_w	Depth of corrosion
d_∞	long term thickness loss due to corrosion
D_L	Length of doubler plate
D_W	Width of doubler plate
D_R	Fillet radius of doubler plate
D_t	Thickness of doubler plate
f	Frequency
N	Number of cycles
O_L	Length of overlap (Edge Distance)
O_W	Width of overlap (Edge Distance)
Q	Shape factor
r_r	Annualized corrosion rate
R_{corr}	Annual wastage rate
s	Stiffener Spacing
S_t	Stiffener thickness
S_L	Stiffener height
S_W	Stiffener flange width
t	time
t_p	Thickness of unstiffened parent plate
t_r	Depth of Corrosion
t_w	Weld leg width
T	Structure age
T_c	Time of Coating Durability
T_e	Time of Exposure
T_t	Transition Time
T_o	Time to corrosion protection system breakdown
V	Wasted steel volume
w	Pit width

$(\Delta K)_p$	Stress intensity factor
α	Pit aspect ratio (a/c)
Δt	Thickness reduction due to Pitting
σ_a	Stress amplitude
τ_c	Time that the coating is effective
τ_t	Time of transition

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Special thanks and acknowledgement are due to many shipbuilders, ship-owners, ship operators and various classification societies who responded to our questionnaire during interviews and meetings.

EXECUTIVE SUMMARY

The US Ship Structures Committee Project, SR-1438, “Design Guidelines for Doubler Plate Repairs of Ship Structures,” was awarded to the Columbia Research Corporation with a subcontract awarded to BMT Designers and Planners, Inc. (D&P), who subcontracted to BMT Fleet Technology Limited (FTL), and U. S. Merchant Marine Academy (USMMA). The objective of this project was to develop a set of guidelines for doubler plate repairs. The project was divided into the following 7 tasks:

- Task 1: Review of current practices and application of doubler plates
- Task 2: Interview Ship-Owners, Shipbuilders and Classification Societies
- Task 3: Perform Buckling Strength Analysis
- Task 4: Perform Fatigue Strength Analysis
- Task 5: Perform Corrosion Analysis of Doubler Plates and Welds
- Task 6: Develop Guidelines for Doubler Plate Repairs
- Task 7: Project Management and Reporting

Tasks 1, 2, and 7 were conducted primarily by D&P. FTL conducted tasks 3 & 4 with contributions from D&P. Task 5 was performed by USMMA. Task 6 was performed with contributions from all three organizations. The main contributors from each organization are:

D&P	**FTL**	**USMMA**
Dr. Pradeep Sensharma	Mandar Avsare	Dr. Yvonne Traynham
Dan Gallagher	Aaron Dinovitzer	
Malcolm Willis		

The guidelines were developed based on the responses received from several ship-owners, shipbuilders and classification societies during personal interviews and also using the results from finite element analyses performed to check buckling and fatigue strength of doubler plates. These guidelines were developed so that the damaged structure regains its original strength with the addition of the doubler plates and the repairs are considered permanent. The results of the analyses performed indicated that the thickness of the doubler plates should be at least 65% of the thickness of the original undamaged plate. Using the results of the finite element analyses and regression analysis the following expression was developed for the minimum corner radius of the doubler plate, which also met the IACS guidelines.

$D_R \geq 85*(D_t / B_t)$

The overlap, doubler plate over original plate, is based upon the results of the finite element analysis and is proposed to be between 50 to 100 mm. Slot welds applied along the stiffeners were found to reduce the hot spot stresses and increase the fatigue strength of the doubler plates. It was also noted that the slot welds are likely to increase the number of fatigue crack initiation sites and care should be taken to ensure the quality of these welds.

1.0 INTRODUCTION

Statistics reveal that corrosion is the number one cause for marine casualties in older ships (Harada et al. 2001). Damage to ships due to corrosion is very common especially in aging ships. The plates and stiffeners suffer corrosion reducing the load bearing capacity of the structure. The consequences of corrosion wastage can be local, but can also be serious in some circumstances. Severe corrosion has resulted in deck cracks across almost the entire ship width and has even resulted in the loss of ships (Wang, 2003).

The use of doubler plates or ‘doublers’ has become routine for temporary ship repairs. It is the preferred method for ships’ structural repairs for plate corrosion due to its relative ease and low cost of installation over the more costly permanent welded plate insert repair. A lack of performance data and engineering design guidance are the reasons that repairs with doublers are currently considered only temporary.

In numerous cases where doublers were used to cover corroded plate it was later discovered that not only was the original structure corroded, but also the doubler plates used to cover them. Doubler plates have previously not been considered to restore structural strength, only maintain local water tightness. Their use has never been accepted as a permanent repair, by either classification societies or by the U.S. Navy, but only as a temporary one until the ship is dry-docked and permanent repairs can be made. In addition to the questionable structural performance that doubler plates provide, there is also concern about crack initiation in the base metal resulting from the peripheral fillet and slot welding of the doubler plate. Therefore, if doubler plates are to be used as permanent repairs the issues of; corrosion, buckling strength, and fatigue and fracture must be addressed. If satisfactory solutions to these problems are found, then a significant savings in repair costs can be made.

A reliability based design approach of doubler plates was studied by Assakkaf et al. (2003). In this study, a reliability-based design model for an unstiffened panel with doubler plate(s) was developed using finite difference (FD) and finite element (FE) approaches. Partial safety factors were also determined to account for the uncertainties in strength and load effect. The First-Order Reliability Method (FORM) was used to develop the partial safety factors.

This Ship Structure Committee (SSC) project was shaped to develop a set of guidelines for designing and applying doubler plate repairs to ship structures. The guidelines were established using the following criteria: various stress analyses, buckling strength, primary stress assessment, corrosion types and rates, weld types, and doubler plate fatigue and fracture assessment. Studying and understanding doubler plate repair performance by comparison to that of the primary hull performance allows critical operational decisions to be made with greater ease and confidence. However, the ultimate goal of this project was to establish the design and limitations on the applications of doubler plate repairs for surface ships.

Hull strapping is also a form of doublers, which are mainly used to increase the strength and stiffness of hull girder structure. This involves attachment of long plates (straps) to the main hull plating and thereby increasing the hull girder sectional modulus. The focus of this study, however, is on the use of doubler plates to repair a corroded patch and will not involve strapping.

2.0 SCOPE OF STUDY

The scope of work for this project was established by the Ship Structure Committee (SSC) as follows:

"This project will consist of a review and summary of classification bodies and/or shipyards, development of analysis and design methods, and development of design/analysis and application guidelines for doubler plate repairs for ship structures. In this study a methodology for designing and using doubler plates will be developed. The use of the methodology will provide quantitative technical rationale (criteria) for the design and limitations on the application of doubler plates as a repair fix for surface ships. The methodology will consist of the following components: stress analysis, buckling strength and residual stress assessment, definition of corrosion types and rates, fatigue and fracture assessment as a result of suing doubler plates. The development guidelines will be applied to representative cases."

The requirements were further described to include the following tasks:

1. Prepare and present a work plan for approval by the Project Technical Committee.
2. Review the commonly used repair fixes for surface ships, and summarize experiences of classification bodies.
3. Develop and validate mathematical and computer models as well as any existing methodologies which explicitly address and predict stress concentrations and residual stresses inherent in this type of repair scheme analysis as well as predicting the buckling strength of doubler plate repairs of ship structural panels.
4. Develop and validate methodologies for predicting the fatigue strength and fracture resistance of doubler plate repairs of ship structural panels.
5. Develop a load application matrix which combines and shows the relationships between the effects of in-plane primary hull girder stresses and lateral localized pressures with the basic plate panel strength characteristics (bending, fatigue, buckling, etc) taking into account various reductions in plating thickness due to corrosion.
6. Identify and incorporate, quantitatively, into the design guidelines, the effects of continuous and intermittent fillet weld strength of doubler plates under cyclic effects of both primary and local lateral loads.
7. Develop guidelines for the design and implementation of doubler plate repairs.
8. Prepare final report providing details of the analysis methodologies and the case studies.

3.0 CURRENT PRACTICES

A review of existing recommendations for the design of doubler plates was completed to define existing support for this repair technique. To collect information regarding the current use of doubler plates D&P contacted several classification bodies, reviewed their rules, and interviewed shipyards and ship owners.

3.1 Classification Societies

3.1.1 Introduction

As part of the review of current industry use of doubler plates, D&P surveyed classification societies and regulatory bodies with regard to their current position on the use of doubler plates. This study involved reviewing the rules and regulations as well as contacting each classification body where possible to interview personnel. The study included a review of American Bureau of Shipping (ABS), Det Nortske Veritas (DNV), Lloyds Register of Shipping (LRS), Germanischer Lloyd (GL), Bureau Veritas (BV), and the International Association of Classification Societies (IACS) rules as well as a review of the sections of the United States Code of Federal Regulations (CFR) relevant to shipping. Personal contacts were made with ABS, DNV, LRS and GL. Some of the following summary will necessarily refrain from identifying the particular class body responsible for the views expressed, since the discussions with class personnel and some of the documents provided pertain purely to internal guidance, not intended to be made available to the public.

3.1.2 Overview

In general, all class societies contacted have similar views toward the application of doubler plates in the repair of ship structure. There are variances at the detail level, but the general guidance and views expressed by the class societies followed IACS Recommendation #47, “Shipbuilding and Repair Quality Standards”. This document provides guidance for the installation of doubler plates but states plainly that doublers are allowed only as a temporary repair solution. The CFR takes no position on the use of doublers, but instead defers judgment of structural adequacy to the office of a recognized classification society. The following discussion therefore is related to the views of the various class societies and IACS.

Since each class society operates according to the general premise that doublers should not be used in repair other than as a temporary measure, none of the societies has formal documentation available to the public regarding the use of doublers in repair other than a basic welding scheme applicable to all doubler use. In the case of temporary doublers, the decisions regarding size, location, thickness, material grade and welding are largely left to the discretion of the surveyor on site. In cases where the seriousness of the situation requires engineering in the development of the specific doublers, the surveyors will send information back to the engineering offices of the respective class for evaluation and approval, but these cases are reviewed individually on a case-by-case basis. In addition, the time frame of "temporary" is somewhat undefined and is also left to a case-by-case interpretation. One class indicated that they are often willing to give a temporary class certificate to give the owner time to get a permanent repair done with replacement inserts. When pressed as to the expected time frame before repair, the answer was that it might be up to a year. This seemed to be similar to the other classes who look for doubler repairs to be made permanent as soon as practicable, but do not require the ship to be taken into drydock immediately. In all cases, it is expected that the doublers will be replaced as soon as the ship can reasonably get into a shipyard or repair facility, but if the original damage is not too severe; the ship is allowed to trade normally for a certain period of time with the doubler in place.

However, although the general rule is to avoid doublers for permanent repair, discussion with the class societies revealed that there are certain cases where some of them will allow permanent doublers to be considered. The allowable areas are defined more by stating the prohibited areas than by giving allowable areas. The external shell and cargo tank boundaries are excluded in all cases, but some internal structure and more of the structure near the peaks may be considered. A more detailed discussion is provided in the summary of discussions with class societies, included below.

It is also important to note that all the class societies accept the use of doublers, in some form, in the process of new construction. Typical applications include landing pads under the feet of equipment placed on decks or at the base of supports landing on the decks, such as small stanchions, side rail posts, etc. In other applications, doublers are explicitly allowed as reinforcement material for the radiused corners of openings in decks and bulkheads in lieu of faceplates, and as intermediate plates between bilge keels and the shell plate. They are also called out as local strengthening for boilers and pressure vessels. While it is difficult to state that such applications would provide justification for the type of use this study is investigating, certain uses called out in the rules are a very different matter. All the class societies contacted indicated that strapping, in the form of wide strips of plating welded to the existing Main Deck plating over at least the midship 0.4L, would be considered as a viable option for increasing the midship section modulus during vessel conversions where an increased section modulus is required. Welding procedures are to follow the standard requirements of the individual class with regard to doublers, but the straps are considered a permanent part of the structure. Another such application is called out by ABS in the shell plating section of their Steel Vessel Rules; increased plate thickness or doubler plates on the sheer strake in way of significant breaks in continuity of the superstructure are allowed.

3.1.3 Installation Guidance

Each of the class societies that provided information on installing doublers indicated some version of a scheme utilizing perimeter fillet welds with an array of slot welds over the area of the doubler. This is similar to the IACS guidelines (See Fig. 3.1), which provide the most complete description of doubler installation. These guidance notes suggest that the doubler plate thickness should be between 1 and 1/3 times the original plate thickness being covered.

The corners of the doubler plate should be rounded to have a radius greater than 50mm and the doubler plate welds are required to have throats greater than 60% of the doubler thickness. While it is noted that the doubler plate should be at least 300 x 300 mm in size the relative sizing of the doubler with respect to a corrosion feature being repaired is not restricted. The recommendations provide some guidance on the sizing of doublers but do not provide any reference indicating how they were derived.

One variation on this received from one of the class societies was a requirement to provide lines of slot welds spaced at no more than 12” in both directions. Another variation received was to have larger slots (6”x 2”) in line with the deck longitudinals with a slot pitch roughly equal to the longitudinal frame spacing. A third variant was essentially the IACS requirement with the addition of slots in line with the plate stiffening in both directions. Otherwise, where the information was provided it was in line with the IACS guidance.

Table 3.1 summarizes guidelines from various classification societies for allowable metal loss in various components of ship structure. This information is of significance to this study since the focus of the investigation is the use of doubler plates as a corrosion repair. This background provides some indication as to the corrosion features that would be repaired. It is noted however that the limits shown in this table are the maximum allowable, thus it is conceivable that a larger corrosion feature might be identified and because of its size be repaired with a doubler. In general, the allowable wastage in plating is 20% of the original plate thickness.

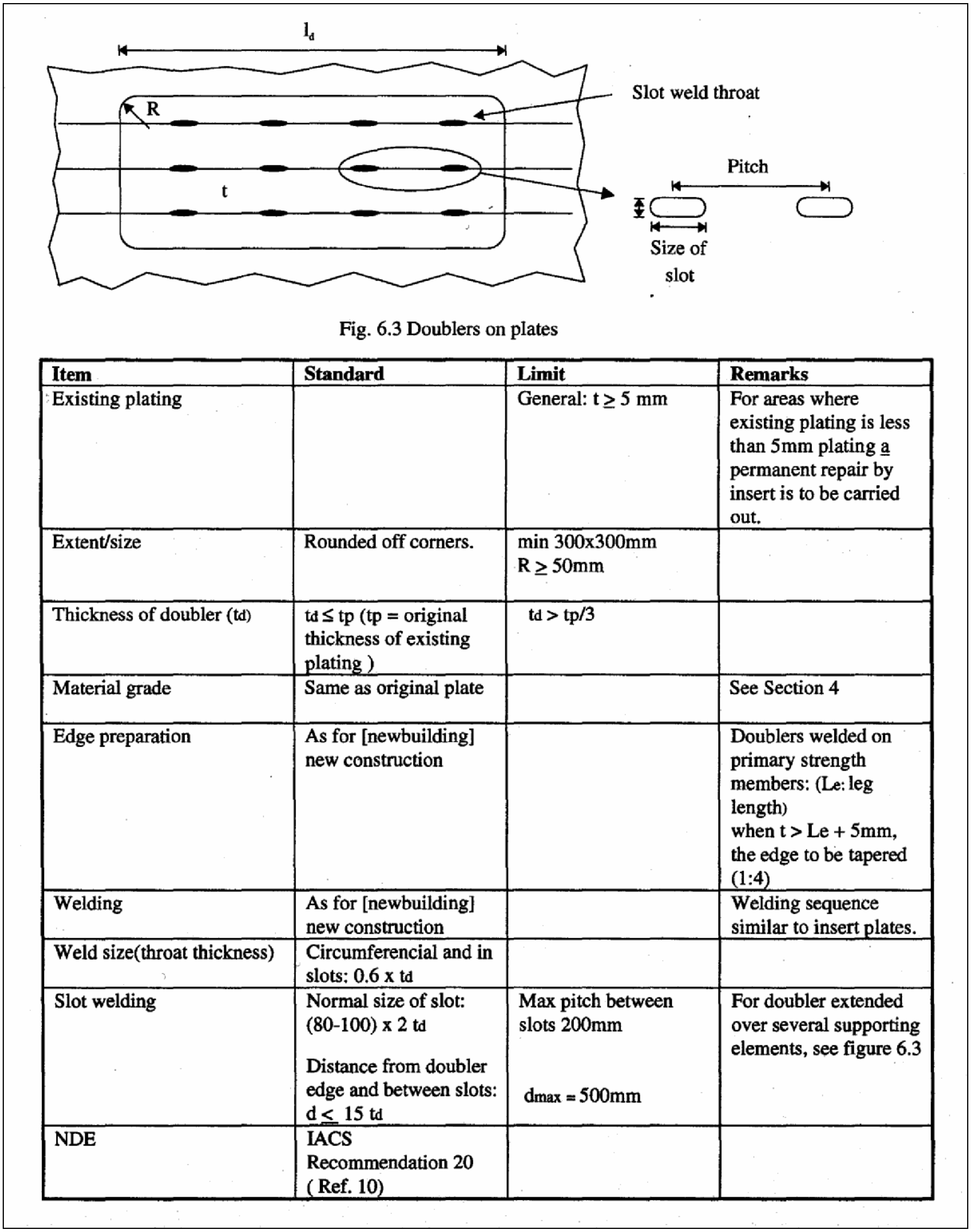


Fig. 6.3 Doublers on plates

Item	**Standard**	**Limit**	**Remarks**
Existing plating		General: t ≥ 5 mm	For areas where existing plating is less than 5mm plating a permanent repair by insert is to be carried out.
Extent/size	Rounded off corners.	min 300x300mm R ≥ 50mm	
Thickness of doubler (td)	td ≤ tp (tp = original thickness of existing plating)	td > tp/3	
Material grade	Same as original plate		See Section 4
Edge preparation	As for [newbuilding] new construction		Doublers welded on primary strength members: (Le: leg length) when t > Le + 5mm, the edge to be tapered (1:4)
Welding	As for [newbuilding] new construction		Welding sequence similar to insert plates.
Weld size(throat thickness)	Circumferencial and in slots: 0.6 x td		
Slot welding	Normal size of slot: (80-100) x 2 td Distance from doubler edge and between slots: d ≤ 15 td	Max pitch between slots 200mm dmax = 500mm	For doubler extended over several supporting elements, see figure 6.3
NDE	IACS Recommendation 20 (Ref. 10)		

Figure 3.1: IACS Guideline for Temporary Doubler Installation

Table 3.1: Structural Scantling Diminution

Component	Lloyds	ABS	BV	NK	GL*	USCG	MSA,UK	Comments
Top Area	10% Plates 15% Longitudinals	15%	20%	20% + 1mm	-	20%	20% or less	-
Bottom Area	10% Plates 15% Longitudinals	20%	20%	20% + 1mm	-	20%	20% or less	-
Deck Plates	10% Plates 15% Longitudinals	20%	20%	20% + 1mm	-	20%	20% or less	-
Shear Strakes	20%	20%	20%	20% + 1mm	-	20%	20% or less	-
Shell Plates	20%	25%	20%	20% + 1mm	-	20%	20% or less	-
Bulge Strake Plates	20%	25%	20%	25%	-	20%	20% or less	-
Bottom Plates	20%	25%	20%	25%	-	20%	20% or less	-
Transverse Bulkhead Plates	20%	25%	15%	25%	-	15%	20% or less	-
Internals including Longitudinals, Girders, Transverse struts, Bulkhead Webs and Stringers, Brackets and Hatch Side Girders	20%	25%	20%	30%	-	30% or 0.14" whichever is less	20% or less	Flanges – 15% Bulkhead Stiffeners: Web- 15% Flange – 10% Bracket 15% (BV)
Under deck Box Girders (Longitudinal or Transverse)	-	15%	-	-	-	-	20% or less	-
Hatch Covers	20%	30%	20%	-	-	20%	20% or less	-

1] IACS doesn't provide any specific limit of scantling diminution in the latest Bulk Carriers Guidelines for Surveys, Assessment and Repair of Hull Structure.
2] Det Norske Veritas (DNV) assesses each scantling of the vessel on the basis of their computer model and generally varies from one component to another in the range of 15-20%.
3] The above limits apply only when the Buckling Strength of the structure is within acceptable limits.
4] Bureau Veritas (BV) limits will apply provided scantling diminution of the structural components in a transverse zone do not exceed limits (10% top or bottom zone and 15% neutral axis zone)
5] Gerrmanischer Lloyds (GL) recommends:

- Section Modulus reduction no more than 10%.
- Large surface reduction for $t \leq 11.5$ mm is 1.5 mm
- For $t\geq 11.5$ mm acceptable reduction = 0.09t+0.45mm (max. 3mm), where,'t' is the plate or original plate thickness.
- The permissible local reduction is no more than 20%

3.1.4 Summary of Additional Remarks and Opinions Expressed During Class Society Interviews

The following are short summaries of additional information received in discussion with the class society personnel.

3.1.4.1 Class Society 1

This class indicated that doublers can be used for permanent repair in some instances, and for temporary repairs it is almost always acceptable. However, where petroleum or any other flammable liquid is being carried, they will not allow doublers to be used for repair on any cargo tank boundary or structure internal to the cargo tanks. Their main concern is safety, since it may be possible to trap liquid or gas between the two plates. This situation could lead to dangerous explosions during welding or during later repair efforts. In ballast tanks, though, they are willing to consider doublers. In fact, for the flanges of stiffeners where material is needed to restore section modulus or increase it, they allow doublers on the stiffener flanges. On plates they are less willing to accept doublers, they normally require the removal and insertion of plates. They are quite concerned about doublers being applied to badly corroded and pitted plate where the ability to weld properly and to create attachment to primary structure of sufficient strength would be in question.

The person interviewed offered his opinion that in his experience, the extra work of preparing the base plate and then doing all the welding required for a doubler makes inserts the more cost effective solution and that as a result doublers are rarely used except in pure compression situations such as pillars, masts, etc. When asked if any work had been done to investigate the structural behavior of doublers he indicated that nothing specific had ever been done. In FE (Finite Element) analysis that included doublers they have merely used the combined plate thickness value based on the assumption that sufficient slot welding will make the two plates act as one.

3.1.4.2 Class Society 2

This class society indicated that before the enhanced survey programs (ESP) were begun, doublers were sometimes allowed for repair, although even then in tankers and bulkers they were not common. They indicated that among the major operators there has been a reluctance to use doublers for a long time, and now there are essentially no places where class will allow doublers to be used as a permanent repair. They indicated that this is certainly the case for major structure in the midship regions, but it was indicated that towards the extremes of the ship it does becomes more of a gray area and doublers may be allowed in these areas at times. However, doublers can be used as a temporary fix for most situations.

The person interviewed indicated that in his opinion doublers are not a very attractive options to owners for whom the prospect of doing the repair twice (doublers though easier than inserts are still not cheap) is an overall expensive option. Therefore, doublers are not often used. However, his opinion is that a doubler can often be an efficient way to make repairs and add material, and that it is worth considering doublers more often as a permanent solution.

3.1.4.3 Class Society 3

This class society provided the internal guidance they use for the application of doubler plates as a permanent repair. The guidelines are as follows:

Doublers shall not be used in the following locations:

- External plating in bottom, sides and upper deck except as given under "doublers may be used".
- Longitudinals on tank- or cargo hold boundaries, such as deck, sides, bottom or longitudinal bulkheads.
- Plating or internals in cargo tanks.
- Boundaries between cargo/bunker tanks and the exterior.
- Deterioration or corrosion on main frames in cargo holds of bulk carriers.
- Cracks in existing plating.
- Doublers should preferably be avoided in the aft peak area, due to the risk for development of vibration cracks along the edges of the doubler.
- Doublers shall not be used in connection with flat bar deck longitudinals within 0.5 L amidships.

Doublers may be used:

> Doublers may be used to a limited extent in permanent repair, if not in conflict with above, as compensation for reduced plate thickness in:

- Internal structure except as described under "doublers not to be used".

- Inner bottom plating.
- Upper deck in peak areas.
- Tween deck plating.

3.2 Shipyards

Shipyards and ship owners were contacted and interviewed to gather information about doubler plate repairs. The list of shipyards and ship owners contacted are listed in Table 3.2 and Table 3.3, respectively.

Two questionnaires were developed by the D&P team of engineers to obtain data on the use of doubler plates in commercial and naval shipbuilding. This was done to ensure that the data collected was consistent. A first contact questionnaire was developed to see whether the shipyard/ ship owners: a) used doubler plates for repair, and b) if they were interested in this study. The second questionnaire was used during the personal interviews. These questionnaires are provided in Appendix A. All the parties surveyed and interviewed were assured their anonymity. Each shipyard / ship owners listed in Table 3.1 and Table 3.2 were contacted and 12 interviews were granted. Most of the other shipyards contacted do not use doubler plates for ship repair.

The questionnaire was prepared in such a way that it would depict the intent of the study and also collect the relevant information that would be used to develop cases for the finite element study. The questionnaire had 3 main sections: section 1 was used to collect data regarding their experience in installing doubler plates, section 2 contained questions regarding their experiences with previously installed doublers. Section 2 was developed to gather condition information on previously installed doublers at the time of dry-dock. The condition of doublers would reflect the performance of such repairs. The last section (section 3) was used to collect general notes and interviewees recommendations regarding the use of doubler plates as a means of permanent/temporary repair. All together twenty six (26) questions were asked.

The interviews were conducted to obtain data on the use of doubler plates with regard to the following details:

- Type of damage repaired
- Location of doubler plate repair
- Expected life span (permanent/temporary)
- Size and thickness of doubler plates
- Doubler plate corner radii
- Use of slot welds
- Shipyard/ship owner recommendation

Table 3.2: List of Shipbuilders Contacted for Interviews

Shipyard	P.O.C.	Address	City	State	Phone		
Bender	Steven Jones	265 S. Water St	Mobile	AL	251-431-8000	251 431-8769	
Atlantic Marine Shipyard	Neville Rush	Dunlap Dr	Mobile	AL	251-690-7100		
Eastern Shipbuilding		2200 Nelson Street	Panama City	FL	850 763-1900		
Tampa Bay	Harry Bell/Steven Derrimine	1130 McClosky Blvd	Tampa	FL	813 248-9310	813 248-7290	
International Ship Repair		1616 Penny lane	Tampa	FL	813 247-1118		
Halter Marine	Sid Mizell	14055 Seaway Rd	Gulfport	MS	228-896-0029		
Halter Marine	Carlos Del Real				228 897-4906		
Bollinger (multiple locations)	Larry Vauclin	806 Bollinger Lane	Amelia	LA	985 631-3600	985 498-0353	
Bollinger (multiple locations)	David Cole	606 Ford Industrial Road	Amelia	LA	985 631-2020	985 637-5341	
Bollinger (multiple locations)	Charlie Herbert		Lockport	LA			
Conrad Industries	AJ Blanchard	110 Brashear Avenue	Morgan City	LA	985 702-0195	985 631-2395	985 397-1615
North American Shipbuilding	Gary Rook		Galliano	LA	985 632-7144		
NORSHIPCO	Jay Matthews Design Engineer	750 W. Berkley Ave.	Norfolk	VA	757-494-4595		
Metro Machine	Scott Henry Project Engineer	Imperial Docks, Foot of Ligon St.	Norfolk	VA	757-494-0778	373-0615 cell	
Colonna's Shipyard	Stephen Walker VP Operations	400 E. Indian River Rd	Norfolk	VA	757-545-2414 Ext 391		Swalker@colonnaship.com
MHI	Jim Calvin QA Manager	543 E. Indian River Road	Norfolk	VA	757-222-4855		
Earl Industries	Cliff Seeley QA Director	826 Mount Vernon Avenue	Portsmouth	VA	904-249-3540 Ext 14		
USCG ELC		2401 Hawkins Road	Curtis Bay	MD	410 762-6000		
Baltimore Marine industries	Hank Jones	600 Shipyard Road	Baltimore	MD	410 477-7652	410 456-9899	
NASSCO	Jay Carson	2789 Harbor Dr	San Diego	CA	619-544-3500		
SouthWest Marine			San Diego	CA	619		
Continental Maritime		1995 Bay Front Street	San Diego	CA	619 234-8851		

Table 3.3: List of Ship Owners Contacted for Interview

Shipyard	**P.O.C.**	**Address**	**City**	**State**	**Phone**	
Alaska Marine Highway System		3132 Channel Dr	Juneau	AK	907-465-3955	
Crowley Marine Services	Mr. Paul Murphy	Pier D, Berths D47-D49	Long Beach	CA	562-491-4752	c)310-849-6719
Crowley		155 Grand Ave	Oakland	CA	510-251-7500	
Baylink Ferries of Vallejo California		Transporation Div. 555 Santa Clara St	Vallejo	CA	877-64-FERRY	
Washington State Ferries	Susan Harris	2911 Second Ave	Seattle	WA	206-515-3460	
Holland America Cruise Lines	Mike Novak	300 Elliot Ave West	Seattle	WA	206-281-3535	
Pacific Fishermen, Inc.	Doug Dixon	5351 24th Ave NW	Seattle	WA	206784-2562	
ConocoPhillips Marine - Polar Tankers	Mr. Frank Lee	600 N. Dairy	Houston	TX	832-379-6216	
Exxon Mobil/SeaRiver Maritime	Pete Weber	13501 Katy Freeway	Houston	TX	281-870-6000	
Canal Barge Company		835 Union St	New Orleans	LA	504-581-2424	
Tidewater		601 Poydras St	New Orleans	LA	800-678-8433	504-568-1010
Crowley Liner Services	Capt. Cole Cosgrove	9487 Regency Square Blvd.	Jacksonville	FL	904-727-2615	904-727-2254
Great Western Steamship Company		18245 SE Federal Hwy	Tequesta	FL	561-747-8888	877-553-3497
Navios	David Elsy	20 Marshall St	South Norwalk	CT	203-354-1300	
Donjon Marine		1250 Liberty Ave	Hillside	NJ	908-964-8812	
Horizon Lines, LLC	Michael Bohlman	1700 Galloping Hill Rd	Kenilworth	NJ	908-259-2803	
Keystone Shipping Company	Pat Finsterbusch	One Bala Plaze East, Ste. 600	Bala Cynwyd	PA	610-617-6922	
Moran Towing Corp.	Michael Nesbitt	444 Collins Dr	Springfield	PA	610-543-3430	
American Automar/Osprey Ship Mgmt	Chris Nette or Paul Hagstrom	6550 Rock Spring Dr	Bethesda	MD	301-571-8500	
Maersk Line Ltd	Capt. Carl Olderich	120 Corporate Blvd. Ste 400	Norfolk	VA	757-852-3222	

A brief summary of the findings from the survey is presented below. These findings are also summarized in Table 3.4; the actual survey responses are provided in Appendix B.

3.2.1 Type of damage repaired

It was found that most of the time doubler plates were used to repair damages due to local wastage, pitting, and cracks. Generally cracks are drilled, welded and then lapped with doublers. In some cases doublers were used to repair the holes. In some cases doublers were used to repair other corroded doublers. In one instance a shipyard mentioned that they had seen 4 layers of doubler plates one on top of another.

3.2.2 Location of doubler plate repair

Most respondents stated that the repair was carried out almost everywhere (except fuel tanks), four shipyards responded saying that they perform repairs only above the waterline.

3.2.3 Expected life span (permanent/temporary)

Seven out of twelve respondents said that they thought the doubler plate repairs were permanent. Four shipyards responded saying doublers would last for the life time of the ship and two put the life-span between 10-15 years. Others stated that the repairs were temporary until the ships were dry-docked for permanent repair.

3.2.4 Size and thickness of doubler plates

According to the responses, size of the doubler plates varied from as small as 3 inch in diameter to a 8’ x 40’ plate. One shipyard responded stating that most repairs in their yard are for doubler plates of 3’ x 3’ or higher. It was found that 1/4 inch, 5/16 inch, and 3/8 inch thick doubler plates were used by most of the shipyards. In some shipyards, doublers up to 1½ inch thick were used. Usually the thickness of the doubler plate is less than or equal to that of the parent plate.

3.2.5 Doubler plate corner radii

All shipyards stated that the corners of the doubler plates were rounded to avoid stress concentrations. The most common corner radius was found to be 3 inches.

3.2.6 Use of slot welds

Most respondents agreed that large and wide doubler plates should be attached using both fillet welds all around the plate and slot welds. The minimum spacing of the slot welds was 12 inches. Some shipyards applied slot welds only on top of the stiffeners supporting the damaged plate. Sizes of the slot welds used by shipyards varied significantly.

For narrow doubler plates, only normal fillet welds are used; 6011/7018 rods were found to be the most common filler material.

3.2.7 Shipyard/ship owner recommendations

Ten out of twelve shipyards responded stating that they would like to see more repairs using doubler plates. They also recommended use of doubler plates for permanent repairs. According to them if the repairs with doubler plates are carried out properly, they do not cause future problems and can last for a long time. Most shipyards thought that doubler plates were the most cost effective way to repair damage. Two shipyards preferred inserts in lieu of doubler plates.

Table 3.4: Summary of Responses Gathered during Interviews

(LW – Local Wastage; P – Pitting; C – Cracks; LB – Local Buckling)

	1	2	3	4	5	6
Date of Interview	5/13/2004	5/12/2004	5/12/2004	6/1/2004	6/2/2004	6/2/2004
Repair/New Build	R	R	R	R	Both	R
Type of Damage	LW, P, C	LW,P	LW, P, C	LW, P, C	LW,C	LW,P
Location	Above WL: Everywhere including stiff flanges	Wet Spaces/ Internal	Above WL, Peak stringers, weather deck, flanges on long. Stack decks	- Mostly exterior shell plating (Bilge, transition at FWD1/4), - some internal bhd - down low near bottom where there is rot	no specific location	Decided by owner
Permanent	Y	Y	Y abv WL, Temp Below WL	Y for inland operation, T for most cases but may stay for 2-3 years until major overhaul	N	N
Expected Life span (years)	15	10	For Life	2 - 3		short
Types of vessel	Barges, tugs, (NO NAVY Ships)	Cargo barges, combatant, amphibious	Barges, tugs, container ships, oil tanker, dredgers, cruise ships (NO NAVY Ships)	small ferries (Uninspected), barges, tow boats, seismic crew boats	Tugs, barges (Inland vessels only)	Shrimp boats only
Thickness of parent plate	-------	-------	-------	-------	-------	-------
Thickness of doubler	1/4-3/4	1/4-3/8		1/4-3/8	1/4-3/8	> 5/16
Doubler size	4' x 6'	Cover damaged area and if possible catch stiff	6" rad to very large	6"x6" to whole bottom	3' x 3' (smallest)	12"x12" to whatever is needed
Doubler corner radii	Y	Y	Y (3" always)	Y (3" routine)	Y	Y
Doubler end tapering	Y	Y	Y	N - unless very thick plate in way of machinery	N	
Slot Weld	Y	Y	Y	Y		Y
Spacing of slot weld - // to stiff	18-24	12	on top of stiff	Match Stiff	Min 12" (set on Long.)	18-24 (on stiff)
Spacing of slot weld perpendicular to stiff.	18-24	12	18 - 12	24	12	same as long. Dir
size of slot weld(inches)	2" dia	1"x2"	3/4 x 1 1/2	2"x1/2"	3/8 or 1/2 x 2 or 3	1t x 3" (fill)
Designers of doubler plates	Shipyard	Shipyard	Shipyard	Owner	shop (foreman), owner	Shop (foreman)
Class Apprv.	ABS	SUPSHIP	ABS, LRS	N	N	N
Weld size (fillet)	plate thickness (t) + 1/32 "	3/16" on 1/4" plate	1/2 thickness + 1/16	1/16 + plate thickness (t)	1/2 thickness + 1/16	1/2 thickness + 1/16
Welding Procedure	flux core, stick weld on old barges		Stagger weld to prevent warpping	wire feed or rods	normal fillet	normal fillet
Filler Material	base metal, flux core-stainless	60/10 low hydrogen rods	70-18 or MIG	6011/7018 rods	--------	--------
Pre/post weld Heat Treatment	No	No	No	No	-------	-------
Recommendation	Y, Cost saving, Good service, no problem if well done	Y, Cost effective, quick, lasts long	Y, Cost effective, Abv WL,	Y, faster, easy to install in areas of shapes	N, (not good for long haul) use only if in a big hurry	N, Prefer inserts (although temp. but once they are they don't come off)
Remarks				Most;y Uninspected vessels. As costly as inserts. Seen cracks in parent plates as doubler is applied.	Seen doubler on Doubler - up to 7 layers in worst case	Uninspected vessels only. Halter Oil Supply boat (Micky Cook) - doubled half the bottom - USCG allowed it.

Table 3.4: Summary of Responses Gathered during Interviews (cont.)

	7	8	9	10	11	12
Date of Interview	6/2/2004	6/2/2004	6/3/2004	6/3/2004	6/3/2004	6/4/2004
Repair/New Build	R	Both	Both	R	R	Both
Type of Damage	LW,C	LW	LW, P, C	C, LW, Pollution Leaks	C, LW, Holes	P, LW, Holes
Location	decks, stern, chines	- Mostly internal - closing plates on struts - compensation for bhd. and gdr. Penetration	Any	Any except Fuel Tank Boundaries. Used on Ballast tank Bhds (ABS approve till next docking).	- never in wet places - M/C foundations, deck fittings	- M/C foundations etc.
Permanent	Y	Y - New build, Reapir	Y - If unregulated	N	N	-------
Expected Life span (years)	For life	For life	For life	Next docking	Short (If minor then up to 2.5 years)	-------
Types of vessel	Inland barges	Supply boats, tugs, casino boats, fishing boats	Barges, Boats, Tugs, Push boats	Supply vessels, Tugs, Push boats	Supply vessels, Tow boats	Supply vessels, Barges, Tugs, Fishing Vessel
Thickness of parent plate	-------	-------	3/8 - 1/2	-------	-------	-------
Thickness of doubler	3/16 - 1/2	1/4 - 1 1/2	1/4 - 1/2 (3/8 most common)	5/16 - 3/8	1/2 - 1	3/8 - 1/2
Doubler size	4" x 4" to 3' x 4'	Very small to 8' x 8'	3" dia to 8' x 40'	18" x 18" to 3' x 3'	up to 2' x2' (if approved by ABS min is 18" x 18")	6" dia to 10' x 40'
Doubler corner radii	Y (2" - 3" typ)	Y (L/8 typ)	Y	Y	Y (3" - 4")	Y - min. 3"
Doubler end tapering	N	Y - if classed	N	N	Y	Y (for thick plates)
Slot Weld	Y (New Build) N (for lapped pl)	Y (New Build) N (for lapped pl)	N (not for thin plates, decision owner driven) - USE STANDARD FILLET	N	Y	Y
Spacing of slot weld - // to stiff	12"	12"	---	---	on top of stiff	12 - 18
Spacing of slot weld perpendicular to stiff.	12"	12"	---	---	8 - 12	12 - 18
size of slot weld(inches)	1t x 3" (fill)	1.5t (wide) x 1"-3" (long)	---	---	1-2 t x 2" (fill solid)	1" x 3"
Designers of doubler plates	Shop (foreman)	Engineering (for New Build) In filed (for small ones)	yard recommends, owners decide	Shipyard	Shipyard, sometimes welder if out in the field	Shipyard (project manager)
Class Apprv.	N	Y (new builds only)	N	N	N	N
Weld size (fillet)	thin plate - 1/4" thick plate - 1 root + 2 extra pass	1/2 thickness + 1/16	--------	--------	--------	--------
Welding Procedure	standard	weld form center out	Normal	Normal	Normal	MIG wire Feed
Filler Material	7018 - 045 wire	7018 rod	6011 or 7018	7018 - wire feed	6011 1st pass + 7018 on cap passes	0.0035 wire
Pre/post weld Heat Treatment	No	Seldom	No	No	No	No
Recommendation	Y, If installed and maintained perform well Prefer INSERTS	Y, If installed and used perform well Much faster and cheaper for outside shell	Y - Except fuel tanks	Y - Except fuel tanks, Temporary only	Y - Great for Temporary fix	Y - Should be used for Permanent repair
Remarks	Mostly - Cut away old and lap weld plate outside. Most owners (95%) want insert not doublers. Local fireboat - 50+ years LAP plate & Doublers All over			Sometimes cut ' X ' in plate befor weldng edges - Prevents cracking		Has never seen one fail

4.0 TECHNICAL APPROACH

4.1 INTRODUCTION

Appropriate guidelines for designing and applying doubler plate repairs to ship structures will be established using as a minimum the following criteria:

- Allowable Stress
- Buckling strength
- Doubler plate weldment fatigue and fracture assessment

The main objective of this project was to investigate the geometric limits of doubler plates for stiffened panels and define appropriate design guidelines for their application.

The project objective related to the development of doubler geometric limits was developed in two steps by considering the fatigue and fracture performance of stiffened panels with doubler plates and considering the buckling resistance of the repaired stiffened panel.

It is noted that the investigation reported herein was limited in its scope and thus involved a number of geometric limits and analysis assumptions including:

- all of the analyses assumed linear elastic structural behavior and thus all of the material was assumed to have the same material properties,
- while some of the reported results are applicable to other structural configurations this study focused on the repair of corrosion features in plating of a stiffened panel,
- the analyses focused on a single angle stiffener / panel geometry (as outlined in Figures 5.1 and 5.2)
- the corrosion features considered were assumed to be flat bottom rectangular thickness reductions in the parent plating,
- the doubler circumferential welds were assumed to have leg lengths equal to the thickness of the doubler plate and thus the throat would be 70 percent of the doubler thickness rather than the IACS recommended 60%, and
- the structural loading considered included independent evaluations of the plate surface pressure, and the effects of longitudinal tension and compression loading.

In all cases the performance of the doubler repair system was considered in terms of its relative behavior. This means that the repair behavior was compared to that of the uncorroded stiffened panel or that of other repair geometries. This method of analysis was selected because the in-service loading of the generic structural assembly being considered can vary widely based upon its location within a vessel, the vessel operational profile and the overall vessel configuration.

4.2 Eigenvalue (Linear) Buckling Analysis

The eigenvalue linear buckling analysis was carried out to estimate the critical buckling load of the structure subjected to compressive loading in the plane of plating. The objective of this element of the presented work is to demonstrate the effectiveness of doubler plates in repairing corrosion damage from the stand point of stiffened panel buckling resistance. The scope of this analysis considered the effect of:

- doubler to base plate thickness ratio,
- corrosion feature location w.r.t. stiffener, and
- doubler plate versus corrosion feature geometry.

4.3 Fatigue and Fracture Analysis

In this element of the project, linear elastic static finite element analysis was carried out to estimate the hot spot stresses at weld toes, when the structure is subjected to tensile and lateral pressure loads. The hot spot stress was chosen as a reasonable indicator of the local stress concentration and thus an indicator of the potential for fatigue and fracture. The objective of the reported work is to demonstrate the sensitivity of:

- doubler corner radius,
- doubler to base plate thickness ratio,
- corrosion feature location w.r.t. stiffener, and
- slot welds.

4.4 Nomenclature

Figures 4.1 and 4.2 illustrate the primary geometric features of the stiffened panel and corrosion feature used in this investigation. The figures are presented to both illustrate the general form of the stiffened panel, and to outline the terminology or abbreviations used to describe the stiffened panels of interest. The parameters used to create and describe the finite element models include:

B_L - Length of stiffened panel
B_W - Width of stiffened panel
B_t - Thickness of stiffened panel
C_L - Length of corrosion feature on stiffened panel (if present)
C_W - Width of corrosion feature on stiffened panel (if present)
C_t - Thickness of remaining ligament at the corrosion feature
O_L - Length of overlap (Edge Distance) = ½ *($B_L - C_L$)

D_L - Length of doubler plate
D_W - Width of doubler plate
D_R - Fillet radius of doubler plate
D_t - Thickness of doubler plate
s - Stiffener Spacing
S_t - Stiffener thickness
S_L - Stiffener height
S_W - Stiffener flange width
t_w - Weld leg length (=D_t)
O_W - Width of overlap (Edge Distance) = ½ *($B_W - C_W$)

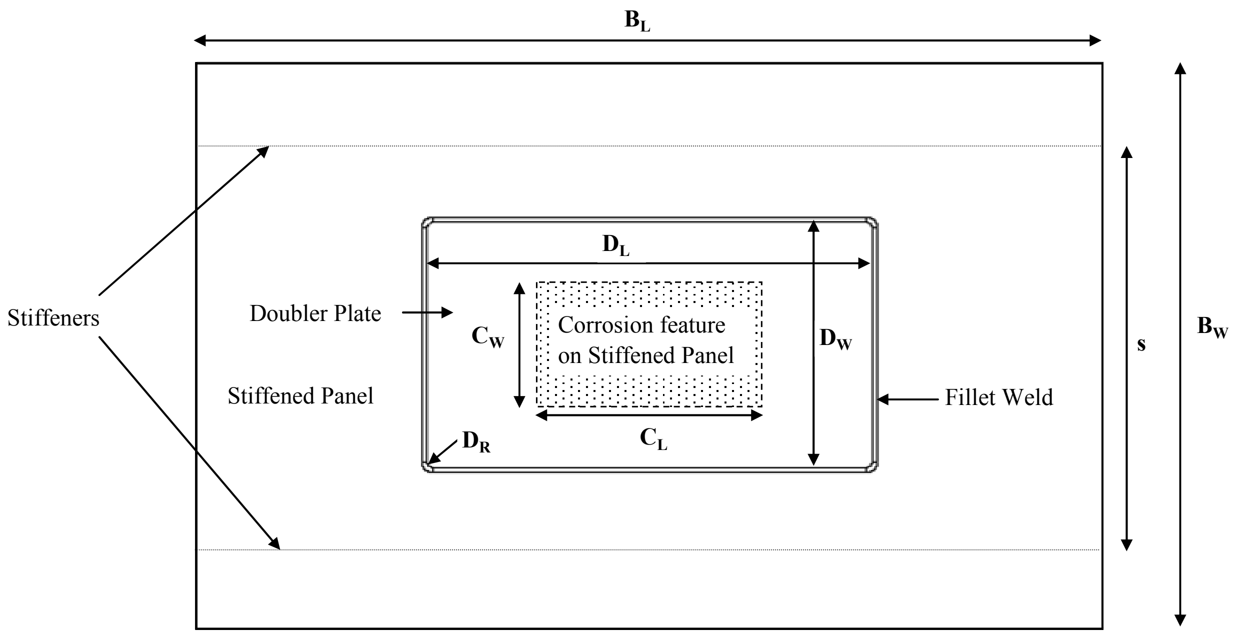


Figure 4.1: Schematic of Stiffened Panel Geometry - Plan View

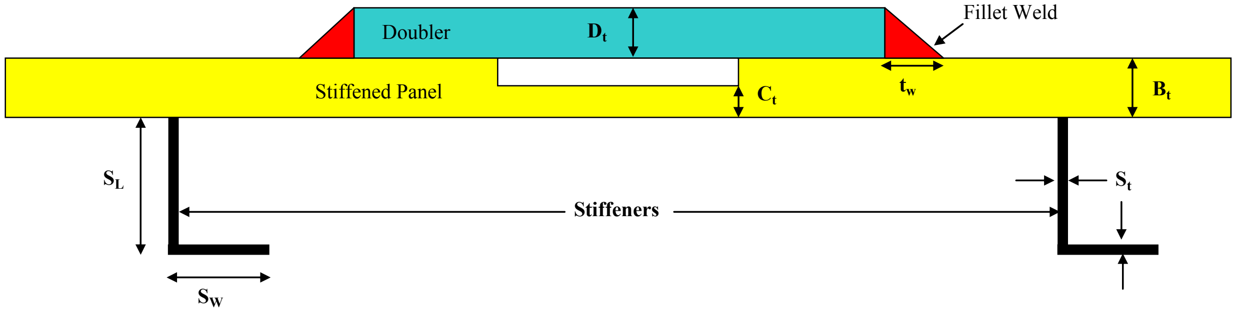


Figure 4.2: Schematic of Stiffened Panel Geometry - Elevation View

5.0 EIGENVALUE LINEAR BUCKLING ANALYSIS

The eigenvalue linear buckling analysis is used to determine buckling (critical) loads at which the stiffened panel structure becomes unstable. There are two techniques available to perform buckling analysis – nonlinear and eigenvalue (or linear) buckling analysis. Eigenvalue (linear) buckling analysis predicts the theoretical buckling strength (the bifurcation point) of an ideal linear elastic structure. This technique is generally used when the structure appears long and slender and is thin-walled. For the current scope of work the eigenvalue buckling technique has been used.

5.1 Finite Element Model

The stiffened panel, doubler plate, stiffeners and welds are modeled using ANSYS Solid45 (8 node brick) elements for the linear buckling analysis. One element through thickness has been used. A refined mesh region with element size t x t x t in the vicinity of weld toe region is used to capture the local stresses in the structure. A sensitivity study was completed to demonstrate the effect of using 20 noded brick elements, for increased accuracy, as opposed to the 8 noded brick elements. This review indicated that the solution time for the 20 noded brick element models was substantially higher with no significant change in the analysis results. Therefore to make the FE modeling process more efficient, 8 noded brick elements have been used. Figures 5.1 and 5.2 illustrate the general geometry and element layout in the FE models used in this investigation along with the coordinate axes. The FE model boundary conditions are illustrated in Figure 5.3.

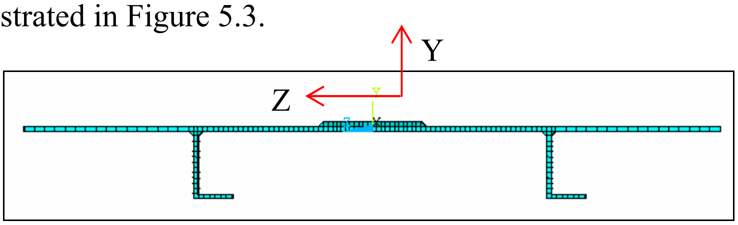


Figure 5.1: FE Model of Corroded Stiffened Plate with Doubler

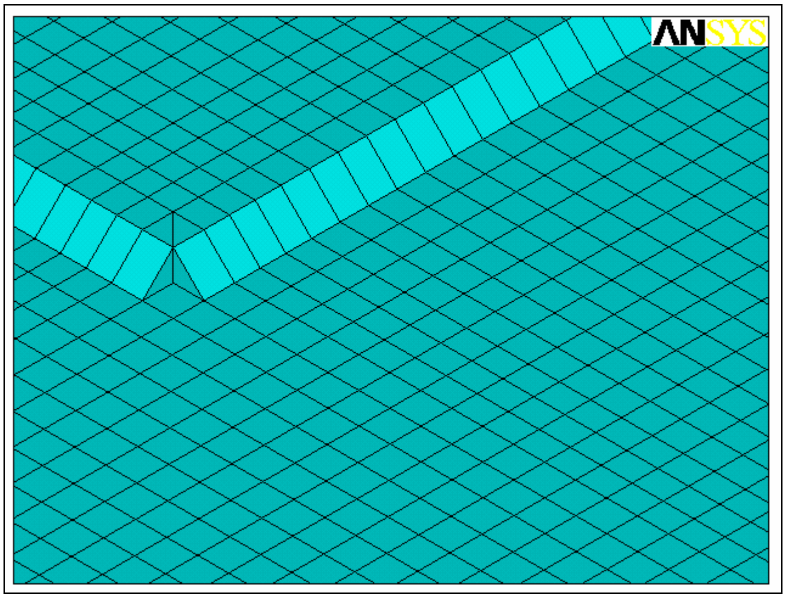


Figure 5.2: Solid Element Mesh Refinement

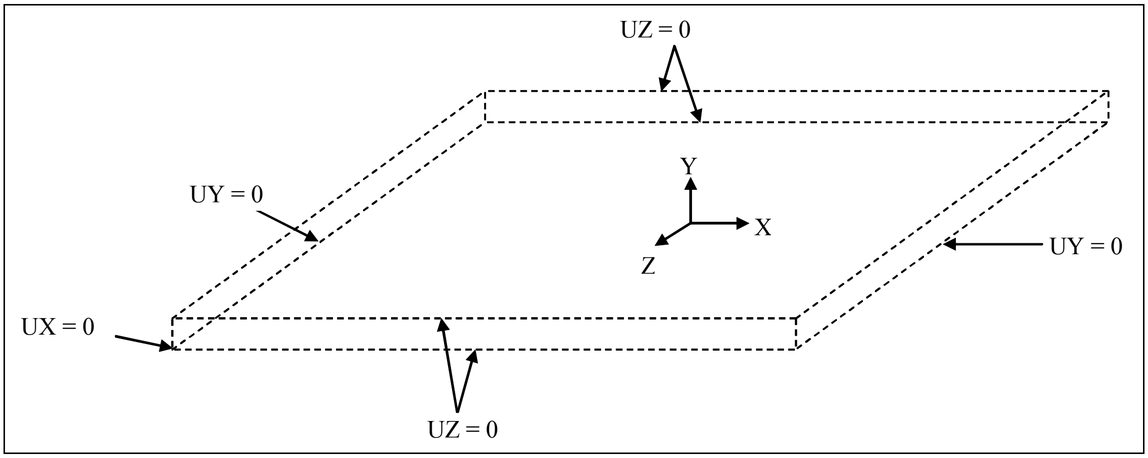


Figure 5.3: Boundary Conditions Applied to the FE Model

5.2 Geometry

In order to develop an understanding of the effects of welding a doubler plate to strengthen or compensate for a corrosion feature, a range of doubler plate thicknesses and corrosion aspect ratios were considered. The corrosion feature aspect ratio is defined as ratio of length of the corroded area to its width. For a constant corrosion feature width (152.4, 457.2 and 762 mm), aspect ratios of 4, 2, 1 and 0.5 were considered. The size (length and width) of the corrosion feature determines the size of the doubler (i.e. the larger the corrosion area the larger the doubler). Based on the design considerations in Section 3.1.3, the doubler edge distances of 25.4, 50.8, 101.6 and 254 mm were considered and doubler thickness was assumed to be 100%, 75% and 50% of the stiffened panel thickness. Table 5.1 illustrates the corroded stiffened panel geometry parameters that are assumed to be constant for the purpose of analysis. Table 5.5 summarizes the geometry variables of stiffened panels investigated in this study along with the buckling strength and load factor results. Intent of this study was to investigate stiffened plate panels with 18”, 24”, 30”, and 36” stiffener spacing. However, due to time and budget limitations this study was restricted to single stiffener spacing of 36”. Mode shapes for few selected cases are shown in Appendix C (Figures C.1 through C.8).

Table 5.1: Constant Stiffened Panel Geometric Parameters Used in Buckling Analysis

Stiffened Plate, mm (inches)			Stiffener ('L'shape)Size, mm (inches)			
Length, B_L	Width, B_W	Thick, B_t	Spacing 's'	Thickness, S_t	Height, S_L	Width, S_W
3657.6 (144.0)	1828.8 (72.0)	12.7 (0.5)	914.4 (36.0)	12.7 (0.5)	177.8 (7.0)	101.6 (4.0)

5.3 Material Model

Due to the linear elastic nature of the investigation, the material behavior model used in this investigation was straight forward. A linear elastic material model based upon modulus of elasticity (E) of 207,000 MPa and Poisson’s ratio of 0.3 is used for the uncorroded and corroded stiffened panel FE models.

5.4 Loading

The stiffened panel finite element models, used to estimate buckling resistance, were subjected to a uni-axial compressive load (x-direction) of 1 N. The nominal applied loads were applied to indicate the sense and direction of the applied loading for the eigenvalue buckling resistance solution process. The eigenvalues calculated and reported by the ANSYS buckling analysis represent buckling load factors (multiples of the applied loading). Therefore, by using a unit applied load, the load factors represent the buckling load.

5.5 Buckling Analysis Results

5.5.1 Effect of Corrosion Features on Buckling Strength of Stiffened Panels – Analysis Baseline

The buckling strength of stiffened panels, with and without corrosion features, was analyzed to develop the desired doubler plate sizing recommendations. The uncorroded stiffened panel buckling load was used to normalize the results generated for the stiffened panels with corrosion features. Table 5.2 provides the geometric parameters describing the uncorroded baseline stiffened panel geometry and defines the buckling load for the panel. Table 5.3

describes the geometry of corroded stiffened panels without doubler plates that were used as reference points in the analysis. These models represent the unrepaired structural systems and the table presents the buckling load for the panels. Due to the presence of metal loss, a corroded plate offers less resistance to buckling than an uncorroded plate. A greater volume or extent of metal loss would be expected to lower the buckling strength of the stiffened panel.

Table 5.2: Buckling Strength of Uncorroded Stiffened Panel

Case No.	**Stiffened Panel, mm**			**Doubler Thickness, mm**	**Corroded Feature, mm**			**Doubler to corrosion edge distance**	**Critical Buckling Load**
	B_L	**B_W**	**B_t**	**D_t**	**C_W**	**C_L**	**C_t**	**mm**	**kN**
A	3657.6	1828.8	12.7	-	-		-	-	2913

Table 5.3: Buckling Strength of Corroded Stiffened Panel without Doubler

Case No.	**Stiffened Panel, mm**			**Doubler Thickness, mm**	**Corroded Feature, mm**			**Doubler to corrosion edge distance**	**Critical Buckling Load**
	B_L	**B_W**	**B_t**	**D_t**	**C_W**	**C_L**	**C_t**	**mm**	**kN**
10a	3657.6	1828.8	12.7	-	152.4	76.2	9.525	-	2864
26a	3657.6	1828.8	12.7	-	457.2	914.4	9.525	-	2633

For the corroded stiffened panel analysis case identified as 10a in Table 5.3, Figure 5.4 illustrates the effect of the corrosion feature and doubler repair on the buckling strength of the stiffened panel. In this sample calculation the doubler plate is 12.7 mm thick and extends 50.8 mm beyond the corrosion feature in length and width (see Tables 5.4 and 5.5 for analysis case 10). It is noted that the addition of a doubler plate to the sample corroded stiffened panels effectively restores the buckling resistance above that associated with the original design. This improvement in buckling capacity is due to the additional cross sectional area (stiffness) afforded by the doubler plate.

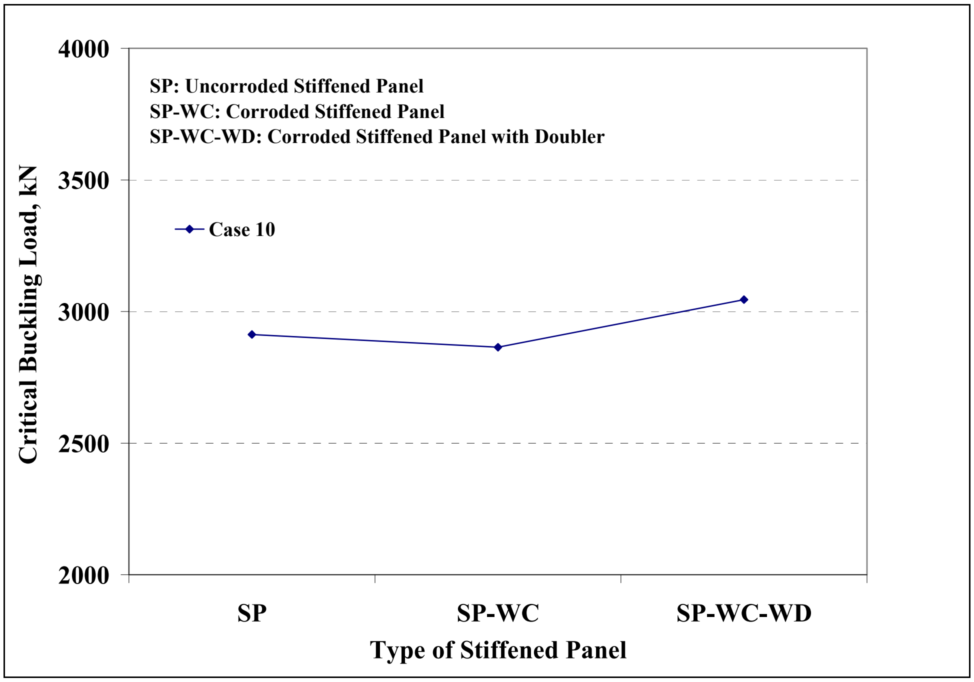


Figure 5.4: Effect of Corrosion and Doubler on Buckling Strength

Also, Table 5.4 illustrates that for a stiffened panel with a constant corrosion feature, the larger the doubler thickness higher the buckling strength. This behavior is only illustrated for two thicknesses and was found generally to be true for most cases analyzed in this study.

Table 5.4: Effect of Doubler Thickness on Buckling Strength

Case No.	Stiffened Panel, mm			Doubler Thickness, mm	Corroded Feature, mm			Doubler to corrosion edge distance	Critical Buckling Load,
	B_L	B_W	B_t	D_t	C_W	C_L	C_t	mm	kN
10	3657.6	1828.8	12.7	12.7	152.4	304.8	9.525	50.8	3045
10b	3657.6	1828.8	12.7	9.525	152.4	304.8	9.525	50.8	3027

With the above general trends illustrated, the sections that follow seek to define the most appropriate doubler dimensions to ensure that the doubler repair fully restores the buckling resistance of the corroded stiffened panel.

5.5.2 Buckling Load Factor

A buckling load factor is defined as the ratio of the critical buckling load of a corroded stiffened panel with doubler to critical buckling of the uncorroded stiffened panel with no doubler under similar loading conditions.

$$\text{Buckling Load Factor} = \frac{\text{Critical buckling load of a corroded base plate with doubler}}{\text{Critical buckling load of a uncorroded base plate with no doubler}}$$

This parameter is used to evaluate the effectiveness of using a doubler on a corroded stiffened panel. For the doubler to be effective the buckling load factor should be greater than or equal to 1 (e.g. the doubler restores the panel structural integrity). Buckling strength and load factor results for stiffened panels containing a range of corrosion features and doubler plates are summarized in Table 5.5. The analyses are completed for a single corrosion feature depth (C_t) with a range of doubler plate thicknesses.

Table 5.5: Buckling Resistance Results for a Corroded Stiffened Panel

Case No.	Doubler Thickness D_t, mm	Corroded Feature, mm			Doubler to corrosion edge distance	Critical Buckling Load	Buckling Load Factor
		Thickness C_t	Width C_W	Length C_L	mm	kN	
1	12.7	9.525	152.4	76.2	25.4	2971	1.02
2	12.7	9.525	152.4	76.2	50.8	3001	1.03
3	12.7	9.525	152.4	76.2	101.6	3059	1.05
4	12.7	9.525	152.4	76.2	254	3125	1.07
5	12.7	9.525	152.4	152.4	25.4	2987	1.03
6	12.7	9.525	152.4	152.4	50.8	3017	1.04
7	12.7	9.525	152.4	152.4	101.6	3074	1.06
8	12.7	9.525	152.4	152.4	254	3130	1.07
9	12.7	9.525	152.4	304.8	25.4	3014	1.03
10	12.7	9.525	152.4	304.8	50.8	3045	1.05
11	12.7	9.525	152.4	304.8	101.6	3099	1.06
12	12.7	9.525	152.4	304.8	254	3142	1.08
13	12.7	9.525	152.4	609.6	25.4	3059	1.05
14	12.7	9.525	152.4	609.6	50.8	3091	1.06
15	12.7	9.525	152.4	609.6	101.6	3117	1.07
16	12.7	9.525	152.4	609.6	254	3176	1.09
17	9.525	9.525	457.2	228.6	25.4	3090	1.06
18	9.525	9.525	457.2	228.6	50.8	3114	1.07
19	9.525	9.525	457.2	228.6	101.6	3132	1.08
20	9.525	9.525	457.2	228.6	254	3286	1.13
21	9.525	9.525	457.2	457.2	25.4	3123	1.07
22	9.525	9.525	457.2	457.2	50.8	3129	1.07
23	9.525	9.525	457.2	457.2	101.6	3145	1.08
24	9.525	9.525	457.2	457.2	254	3332	1.14
25	9.525	9.525	457.2	914.4	25.4	3150	1.08
26	9.525	9.525	457.2	914.4	50.8	3161	1.09
27	9.525	9.525	457.2	914.4	101.6	3188	1.09
28	9.525	9.525	457.2	914.4	254	3469	1.19
29	9.525	9.525	457.2	1828.8	25.4	3311	1.14
30	9.525	9.525	457.2	1828.8	50.8	3353	1.15
31	9.525	9.525	457.2	1828.8	101.6	3457	1.19
32	9.525	9.525	457.2	1828.8	254	4129	1.42
33	6.35	9.525	762	381	25.4	3193	1.1
34	6.35	9.525	762	381	50.8	3228	1.11
35	6.35	9.525	762	381	101.6	3256	1.12
36	6.35	9.525	762	381	254	1878	0.64
37	6.35	9.525	762	762	25.4	3143	1.08
38	6.35	9.525	762	762	50.8	2798	0.96
39	6.35	9.525	762	762	101.6	2241	0.77
40	6.35	9.525	762	762	254	1288	0.44

Table 5.5: Buckling Resistance Results for a Corroded Stiffened Panel (cont.)

Case No.	Doubler Thickness D_t, mm	Corroded Feature, mm			Doubler to corrosion edge distance	Critical Buckling Load	Buckling Load Factor
		Thickness C_t	Width C_W	Length C_L	mm	kN	
41	6.35	9.525	762	1524	25.4	2296	0.79
42	6.35	9.525	762	1524	50.8	2097	0.72
43	6.35	9.525	762	1524	101.6	1761	0.6
44	6.35	9.525	762	1524	254	1109	0.38
45	6.35	9.525	762	3048	25.4	1890	0.65
46	6.35	9.525	762	3048	50.8	1719	0.59
47	6.35	9.525	762	3048	101.6	1434	0.49
48	6.35	9.525	762	3048	254	881	0.3
33a	12.7	9.525	762	381	25.4	3289	1.13
34a	12.7	9.525	762	381	50.8	3330	1.14
35a	12.7	9.525	762	381	101.6	3349	1.15
36a	12.7	9.525	762	381	254	3413	1.17
37a	12.7	9.525	762	762	25.4	3356	1.15
38a	12.7	9.525	762	762	50.8	3398	1.17
39a	12.7	9.525	762	762	101.6	3422	1.17
40a	12.7	9.525	762	762	254	3517	1.21
41a	12.7	9.525	762	1524	25.4	3566	1.22
42a	12.7	9.525	762	1524	50.8	3636	1.25
43a	12.7	9.525	762	1524	101.6	3715	1.28
44a	12.7	9.525	762	1524	254	4069	1.4
45a	12.7	9.525	762	3048	25.4	4789	1.64
46a	12.7	9.525	762	3048	50.8	4692	1.61
47a	12.7	9.525	762	3048	101.6	4672	1.6
48a	12.7	9.525	762	3048	254	4649	1.6
34b	9.525	9.525	762	381	50.8	3375	1.16
38b	9.525	9.525	762	762	50.8	3299	1.13
42b	9.525	9.525	762	1524	50.8	3589	1.23
46b	9.525	9.525	762	3048	50.8	4040	1.39
49	12.7	6.35	762	3048	50.8	2075	0.71
50	12.7	7.7	762	3048	50.8	3114	1.07
51	12.7	11.7	762	3048	50.8	5234	1.8
52	9.525	6.35	762	3048	50.8	1887	0.65
53	9.525	7.7	762	3048	50.8	2816	0.97
54	9.525	11.7	762	3048	50.8	4639	1.59
55	6.35	6.35	762	3048	50.8	1501	0.52
56	6.35	7.7	762	3048	50.8	1591	0.55
57	6.35	11.7	762	3048	50.8	1881	0.65

5.5.3 Effect of Doubler Size and Thickness

For Cases 1 to 16 (Table 5.5), where the thickness of doubler is equal to thickness of stiffened panel, the buckling load factor is greater than 1 indicating that the strength of the corroded stiffened panel is restored through the application of a doubler plate (Figure 5.5). Also it can be seen that increasing corrosion aspect ratio has no significant effect on the strength of the corroded stiffened panel.

For doublers with thickness equal to the nominal thickness of the parent material and a constant corrosion feature aspect ratio, Figure 5.5 illustrates that as the doubler size increases there is a slight increase in the buckling strength of the corroded stiffened panel.

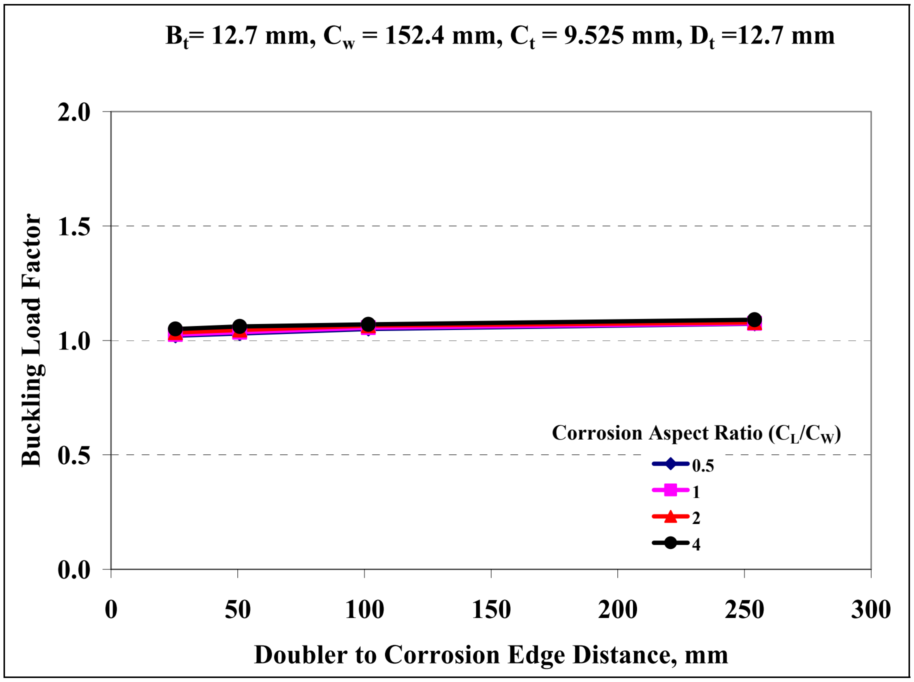


Figure 5.5: Buckling Load Factor for D_t = 12.7 mm; C_W = 152.4 mm

Based upon the results of analyses 17 to 32 (Table 5.5), where the thickness of the doubler plate is equal to the thickness of corroded feature, the buckling load factor is always greater than 1 indicating that the strength of the corroded stiffened panel is restored through the application of the doubler (Figure 5.6). Over the range of values evaluated, as the corrosion aspect ratio and doubler size increases, the buckling strength of the corroded stiffened panel increases slightly. Also for a constant corrosion aspect ratio, the buckling strength increases with increase in doubler edge distance. The effect of doubler edge distance on the buckling strength of stiffened panel is more pronounced for corrosion aspect ratio of 4.

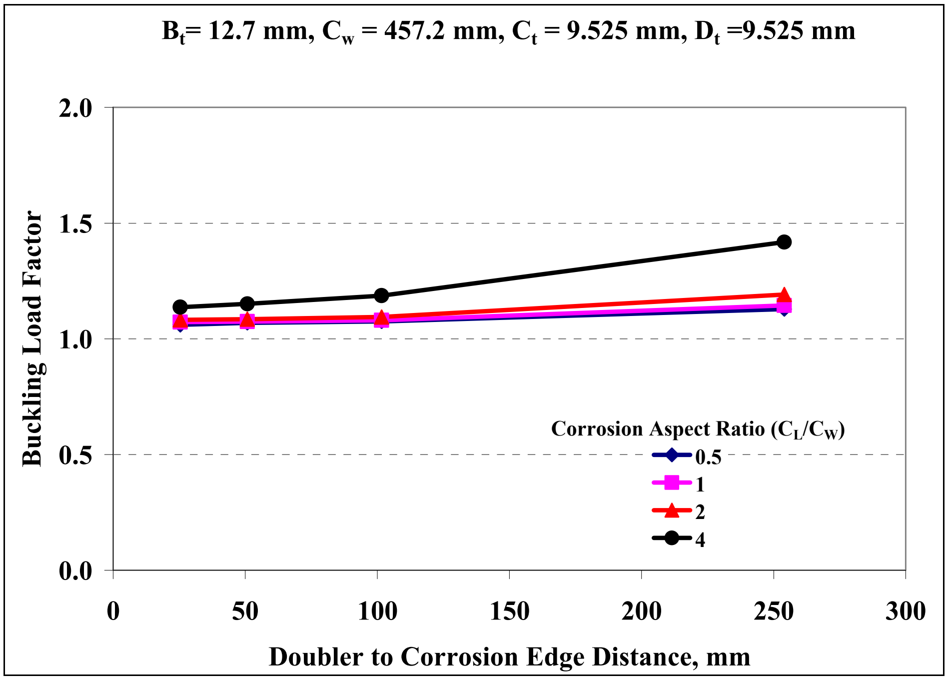


Figure 5.6: Buckling Load Factor for $D_t = 9.525$ mm; $C_W = 457.2$ mm

For Cases 33 to 48 (Table 5.5) where the thickness of doubler plate is less than the thickness of the remaining ligament of the corroded feature, Figure 5.7 illustrates that the buckling load factor for corrosion aspect ratios of 2 and 4 (Corrosion $_{\text{length}}$ > Corrosion $_{\text{width}}$) is less than 1 indicating ineffectiveness of the doubler in repairing the corrosion damage. As the corrosion aspect ratio and doubler size increases, the buckling strength of the corroded stiffened panel decreases significantly. This suggests that having a doubler plate that is significantly larger in size than the corrosion feature but thinner than the corroded patch, is not an effective repair solution. For corrosion aspect ratios of 0.5 and 1 (Corrosion $_{\text{length}} \leq$ Corrosion $_{\text{width}}$), a small size doubler is more effective than a larger doubler.

Overall the buckling strength of the corroded stiffened panel drops when thickness of the doubler is less than the thickness at the corrosion feature.

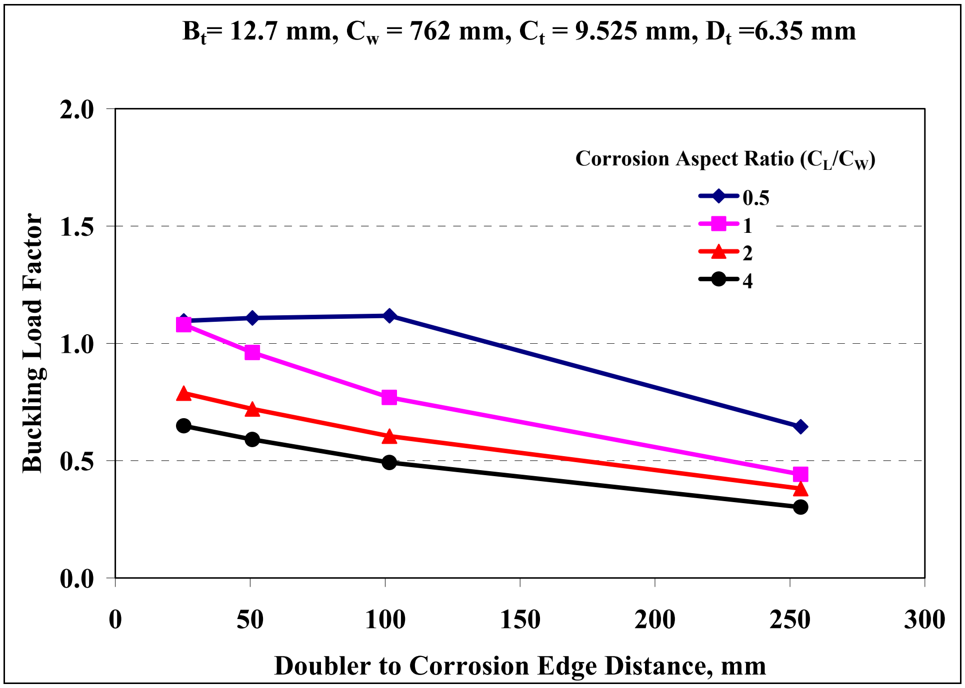


Figure 5.7: Buckling Load Factor for D_t = 6.35 mm; C_W = 762 mm

For scenarios where the buckling load factor is less than 1 (Figure 5.7), indicating ineffectiveness of the doubler, a thicker doubler can be used to provide the necessary buckling strength to the corroded stiffened panel. Figure 5.8 illustrates effectiveness of using a thicker doubler plate.

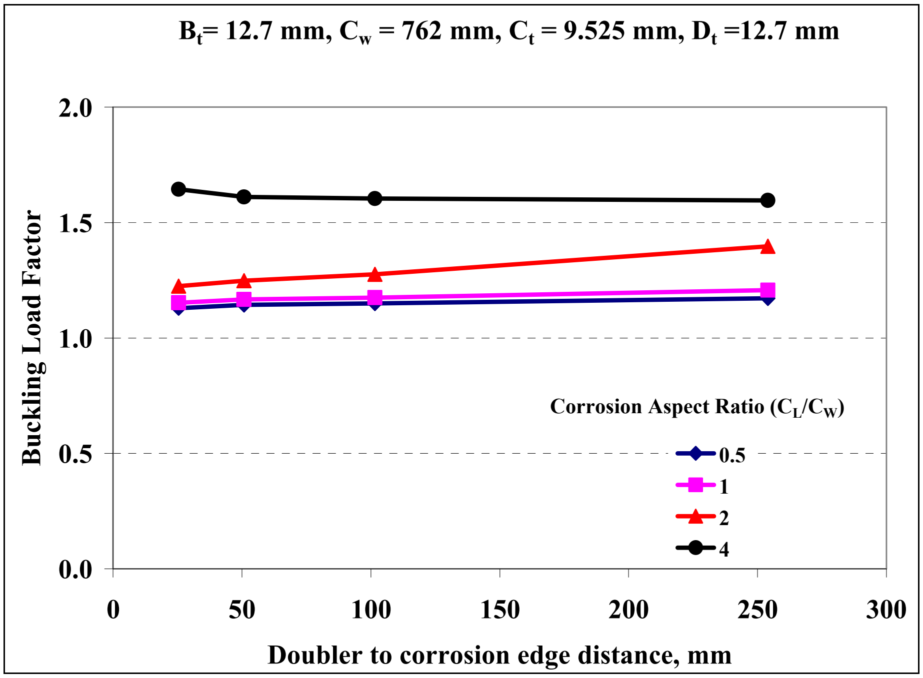


Figure 5.8: Buckling Load Factor for D_t = 12.7 mm; C_W = 762 mm

Based upon the results presented in Table 5.5 and Figures 5.5 through 5.8, it is apparent that, for doubler thickness of 12.7 and 9.525 the doubler edge distance, over the range of values investigated is not a significant factor affecting the buckling resistance. Considering issues related to cost and space for welding for larger doublers, a doubler edge distance of 50.8 mm is recommended. It is also noted that the doubler plate geometries investigated did not demonstrate the need for slot welds, however, these additional doubler to base plate attachments may be necessary for larger or deeper corrosion features.

5.5.4 Doubler Thickness Factor

The following section is included to define the doubler thickness required to repair a stiffened panel corrosion feature. To study the effect of loss of stiffened panel thickness on its buckling strength, 'Doubler Thickness Factor' has been introduced. Doubler Thickness factor is defined as:

$$\text{Doubler Thickness Factor} = \frac{\text{Doubler Thickness}}{\text{Uncorroded Stiffened Panel Thickness - Corroded Feature Thickness}}$$

The calculated doubler thickness factors are listed in Table 5.6. The ranges of parameters listed in the Table 5.6 were selected to permit evaluation of the effect of doubler plate thickness on the effectiveness of corrosion repair scenarios. Figure 5.9 illustrates the effect of the doubler thickness factor on buckling load factor of 762 mm wide corroded stiffened panels.

Table 5.6: Doubler Thickness Factor

Case Type	Uncorroded Stiffened Panel thickness (mm)	Doubler Plate thickness (mm)	Corrosion feature thickness (mm)	Doubler thickness factor
1	12.7	12.7	9.525	4
2	12.7	9.525	9.525	3
3	12.7	6.35	9.525	2

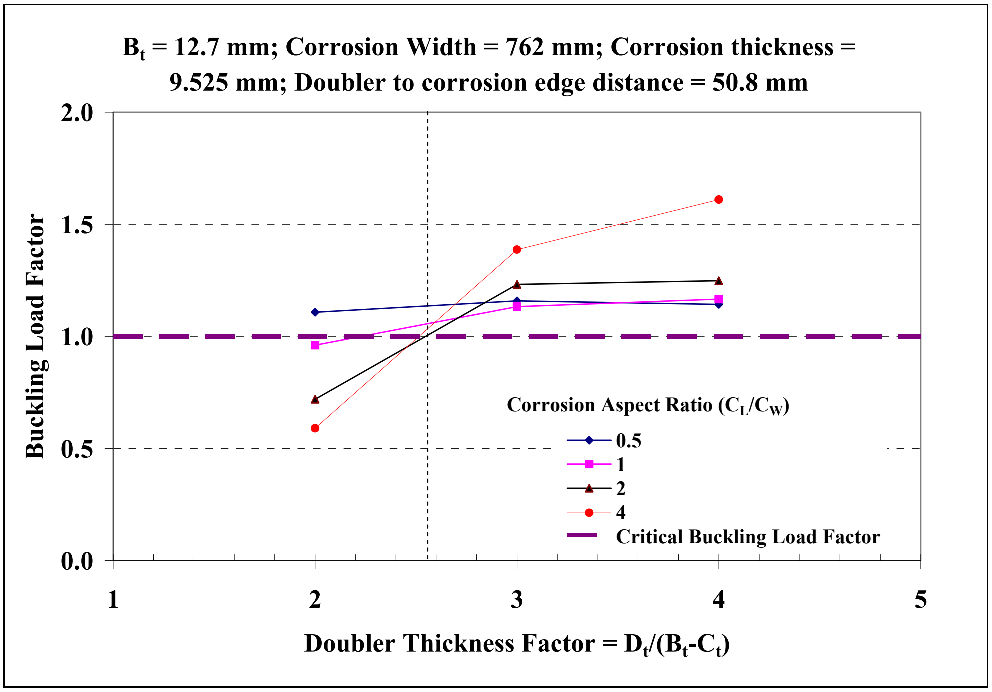


Figure 5.9: Effect of Doubler Thickness Factor

Increasing the doubler thickness increases the buckling strength of the corroded stiffened panel. Based upon the results shown in Figure 5.9, it is suggested that the most appropriate doubler thickness can be defined based upon doubler thickness factor. For effective buckling strength it is suggested that for a corroded stiffened panel doubler thickness factor be more than 2.6. This would mean that if the thickness of the corroded patch were 9.525mm then the thickness of doubler plate should be at least 8.255mm [2.6*(12.7-9.525)] to restore the buckling strength. Doubler plate thickness for a corroded patch of 6.35mm would need a doubler that is 16.51mm thick.

5.6 Effect of Corrosion

Figure 5.10 illustrates the effect of thickness of the corroded feature on buckling load factor of corroded stiffened panel. As the metal loss increases beyond 25%, the buckling strength of stiffened panel is reduced drastically.

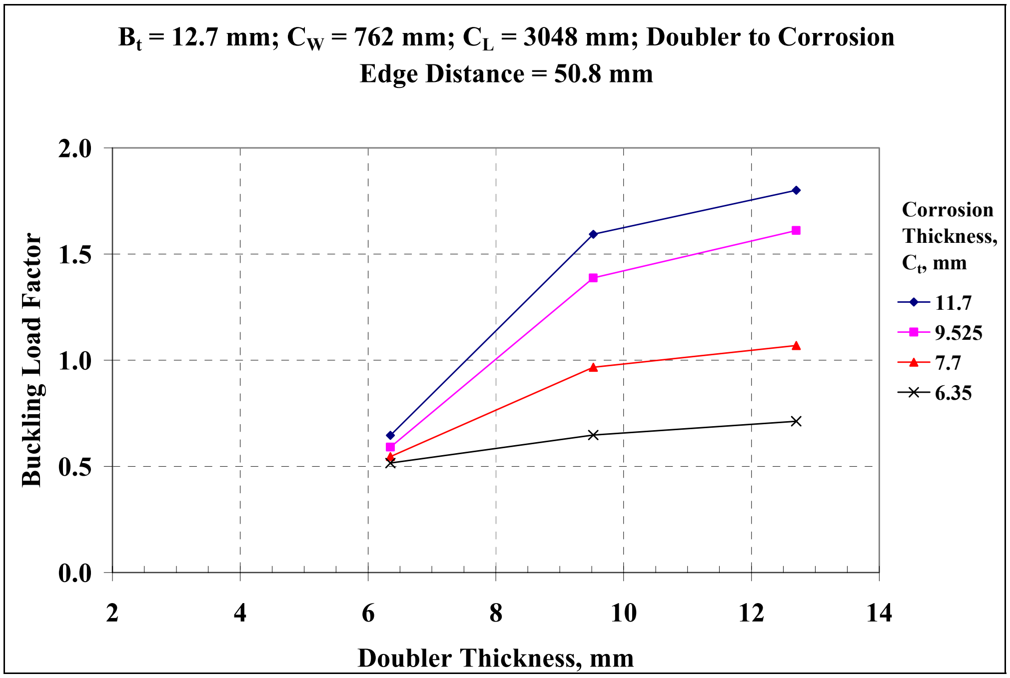


Figure 5.10: Effect of Corrosion

Stiffened panels with corrosion features greater than 25% of their plate thickness should be repaired permanently and use of doubler plate is not recommended. For metal loss less than or equal to 25%, the figure above indicates that an 8mm doubler thickness would restore the effectiveness of the panel with regards to buckling resistance. Based upon this result it is suggested that the doubler thickness be at least 65% (approx 8mm / 12.7mm) of the stiffened panel plate thickness.

5.7 Conclusions for Buckling Analysis

Based upon the cases analyzed and the results that were generated, the following conclusions for restoring the buckling strength of a stiffened plate with a doubler are presented:

- For doubler thickness greater than or equal to the thickness of the corroded patch (Dt=12.7 mm and 9.525 mm), an increase in corrosion aspect ratio has no adverse effect on the buckling strength of the corroded stiffened panel.

- For doubler thicknesses less than the thickness of the corroded patch (Dt=6.35 mm), the increase in corrosion feature aspect ratio lowers the buckling strength of the repaired corroded panel.

5.8 Doubler Recommendations for Corroded Stiffened Panel

Based upon the analyses completed and the results that were generated, the following recommendations for restoring the buckling strength of a stiffened plate with a doubler are presented:

- For metal loss greater than 25% of the parent plate thickness, the use of doublers is not recommended.
- To restore the buckling resistance of a stiffened panel, the doubler plate thickness should be greater than the larger of:
    - 65% of the original stiffened panel plate thickness ($D_t > 0.65*B_t$)
    - thickness determined by the doubler thickness factor 2.6 (i.e. $2.6*(B_t - C_t)$)
- The doubler size (length and width), doubler plate edge distance can be any value but care should be taken to minimize the size of the doubler plate. It is recommended that a 50mm (2 inch) corrosion feature to doubler edge distance be used. It is noted that larger doubler plates will need slot welds to ensure stability.

6.0 FATIGUE AND FRACTURE ANALYSES

6.1 Effect Of Doubler Corner Radius On Fatigue And Fracture Resistance

6.1.1 Finite Element Model

The stiffened panel, doubler plate, stiffeners and welds are modeled using ANSYS Solid186 (20 node brick) elements for static analysis. One element through thickness has been used [DNV 2000]. A refined mesh region with element size t x t x t in the vicinity of weld toe region is used to capture the stresses in the structure. Figures 6.1 and 6.2 illustrate the general geometry and element layout in the FE models used in this investigation along with the coordinate axes. Figures 6.2 and 6.3 contrast the model meshing for differing doubler corner radii. The FE model boundary conditions are illustrated in Figure 6.4.

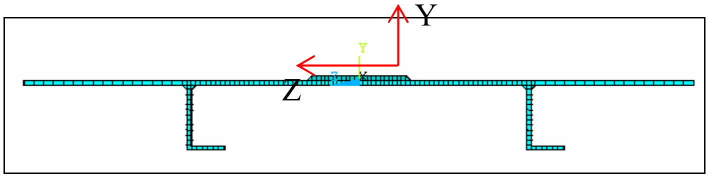


Figure 6.1: FE model of Stiffened Panel with Doubler Plate

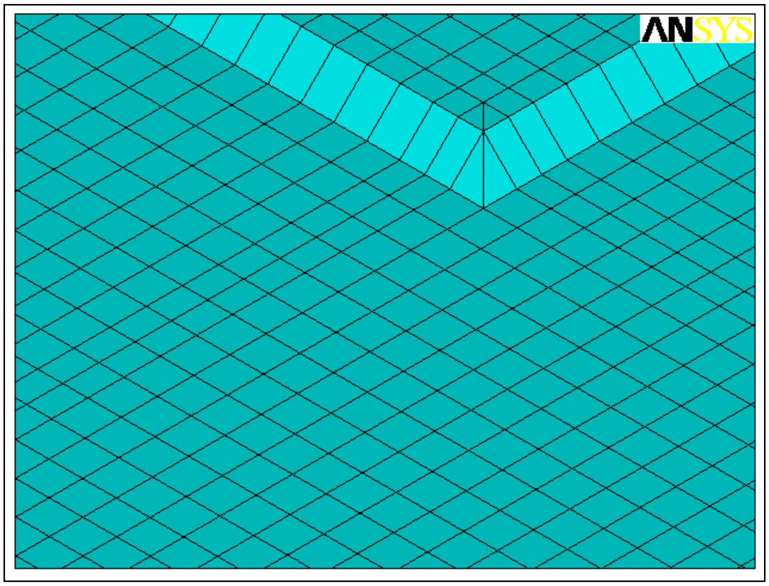


Figure 6.2: Doubler with Sharp Corner

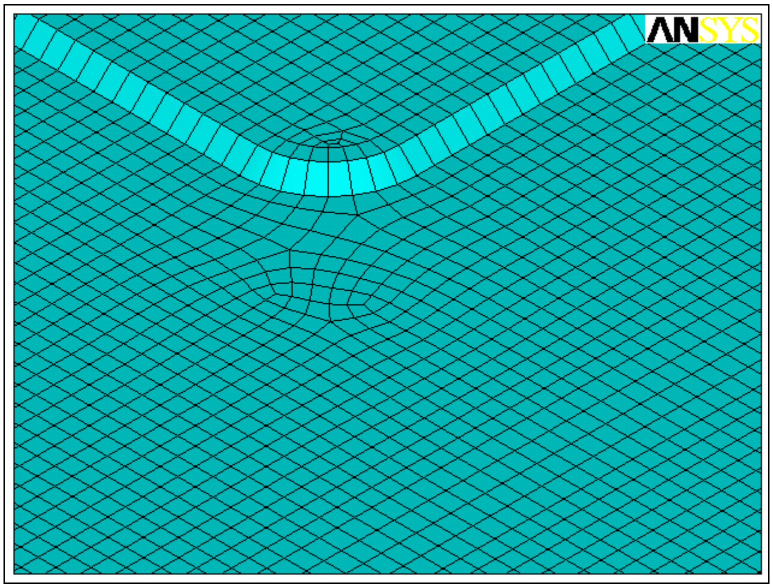


Figure 6.3: Doubler with Corner Radius

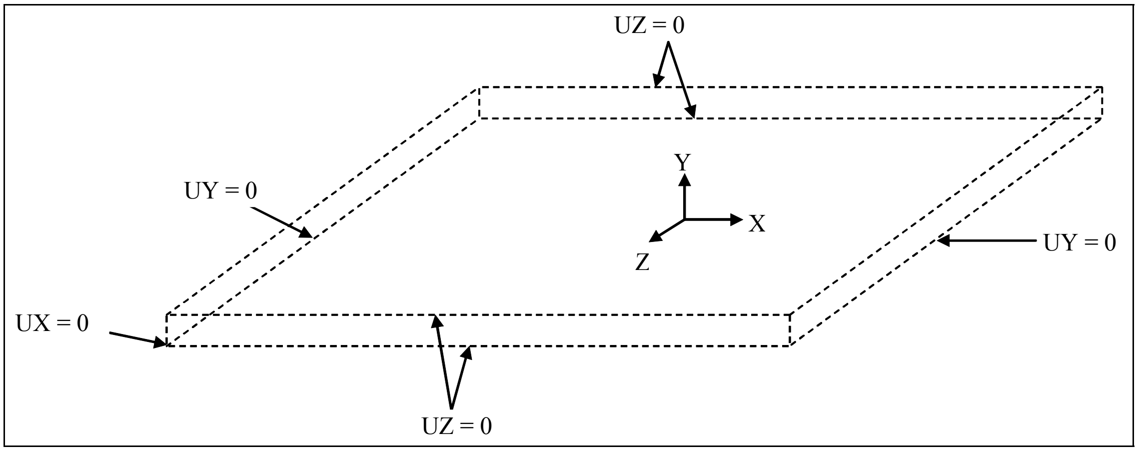


Figure 6.4: Boundary Conditions Applied to the FE Model

6.1.2 Geometry

In order to develop an understanding of the effects of corner radius on stress distribution of the stiffened panel, a range of doubler and doubler plate corner radii were considered. Doubler thickness is assumed to be 100%, 75% and 50% of stiffened panel thickness. Doubler corner radiuses of 50.8, 101.6 and 152.4 mm were considered. The stiffened panel is assumed to be uncorroded. Table 6.2 summarizes the geometries investigated and results for hot spot stress analysis.

6.1.3 Material Model

Due to the linear elastic nature of the investigation, the material behavior model used in this investigation was straight forward. A linear elastic material model based upon modulus of elasticity (E) of 207,000 MPa and Poisson's ratio of 0.3 is used for the uncorroded and corroded stiffened panel FE models.

6.1.4 Hot Spot Stress Analysis

A hot spot stress analysis approach is used to consider the expected relative fatigue performance of the stiffened panel. The hot spot stress approach considers the principal stress as affected by all stress concentration factors except that induced by the weld toe geometry. In these analyses, the hot spot stress is calculated at the weld toe locations P1 (at corner of doubler) and P2 (center of doubler) for doubler corner radii of 25.4, 50.8 and 152.4 mm.

The stress at weld toe is linearly extrapolated from those at distance t/2 and 3t/2 from weld toe, where,'t' is the thickness of stiffened panel. Figure 6.5 illustrates the hot spot stress locations (P1 and P2) considered for analysis.

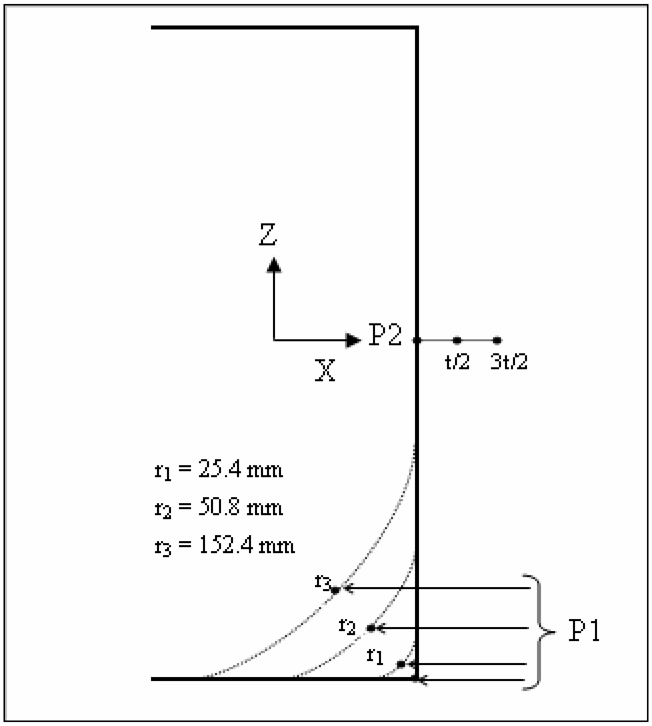


Figure 6.5: Hot Spot Stress Locations

6.1.5 Loading

The stiffened panel is subjected to a uni-axial tensile edge pressure (x-direction) of 75.84 MPa. Since the objective of this work is to develop an understanding of the nature of the stress concentration, or damaging effects of the doubler corner radius, the applied loading can be considered based upon a notional or unit applied loading.

6.1.6 Hot Spot Stress Results

The results for hot spot stress analysis for various geometries are summarized in Table 6.1. To evaluate the fatigue life at location P1, S-N approach is used. The basic design S-N curve is given as:

$$\log N = \log a - m \log \Delta\sigma$$

where N is the predicted number of cycles to failure for stress range
$\Delta\sigma$ is the stress range
m is the negative inverse slope of S-N curve = 3
$\log a$ is the intercept of log N-axis by S-N curve = 13

The details presented are based upon assumptions outlined in Table 2.11 of DNV standard for fatigue assessment of ship structures. As the corner of the doubler is most likely location for crack initiation, fatigue assessment is carried out at location P1 and cycles to failure is shown in Table 6.1.

Stress plots for few selected cases are shown in Appendix C (Figures C.9 through C.12).

Table 6.1: Hot Spot Stress Summary

Case No	Stiffened Panel, mm			Stiffener Size, mm				Doubler Size, mm				Hot Spot Stress 'σ_X' MPa		Cycles to failure
	B_L	B_W	B_t	s	S_L	S_W	S_t	D_L	D_W	D_t	D_R	P1	P2	P1
A	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	12.7	0	151.67	109.69	2.87E+06
1A	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	12.7	50.8	119.99	111.65	5.79E+06
2A	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	12.7	101.6	107.22	113.76	8.11E+06
3A	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	12.7	152.4	104.39	117.60	8.79E+06
B	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	9.525	0	134.94	109.03	4.07E+06
4B	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	9.525	50.8	112.14	109.61	7.09E+06
5B	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	9.525	101.6	102.96	111.29	9.16E+06
6B	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	9.525	152.4	99.01	114.58	1.03E+07
C	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	6.35	0	114.97	104.94	6.58E+06
7C	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	6.35	50.8	104.09	105.68	8.87E+06
8C	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	6.35	101.6	96.06	106.77	1.13E+07
9C	3657.6	1828.8	12.7	914.4	177.8	101.6	12.7	1016	508	6.35	152.4	93.04	109.17	1.24E+07
G	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	9.525	0	160.79	108.04	2.41E+06
10G	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	9.525	50.8	120.36	109.96	5.74E+06
11G	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	9.525	101.6	105.75	111.87	8.46E+06
12G	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	9.525	152.4	103.41	115.47	9.04E+06
H	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	7.144	0	140.00	107.85	3.64E+06
13H	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	7.144	50.8	113.78	108.06	6.79E+06
14H	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	7.144	101.6	104.28	109.58	8.82E+06
15H	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	7.144	152.4	99.85	112.67	1.00E+07
I	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	3.572	0	104.82	100.01	8.68E+06
16I	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	3.572	50.8	97.15	101.02	1.09E+07
17I	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	3.572	101.6	91.78	101.74	1.29E+07
18I	3048	1524	9.525	762	152.4	101.6	9.525	1016	508	3.572	152.4	89.86	103.50	1.38E+07

6.1.6.1 Effect of Doubler Corner Radius on Fatigue Strength of Stiffened Panel at Location P2

As the corner radius of the doubler is increased, the net cross sectional area of the doubler at its leading edge reduces. Based upon the reduction in cross sectional area, the weld toe stress at location P2 increases with increase in doubler corner radius (Figures 6.6 and 6.7). This would serve to reduce the fatigue life of the doubler plate system. It is noted that the increase in hot spot stress at location P2 is less than 10%, for the cases investigated, and thus may not be a significant factor in the deign of doubler plate repair systems.

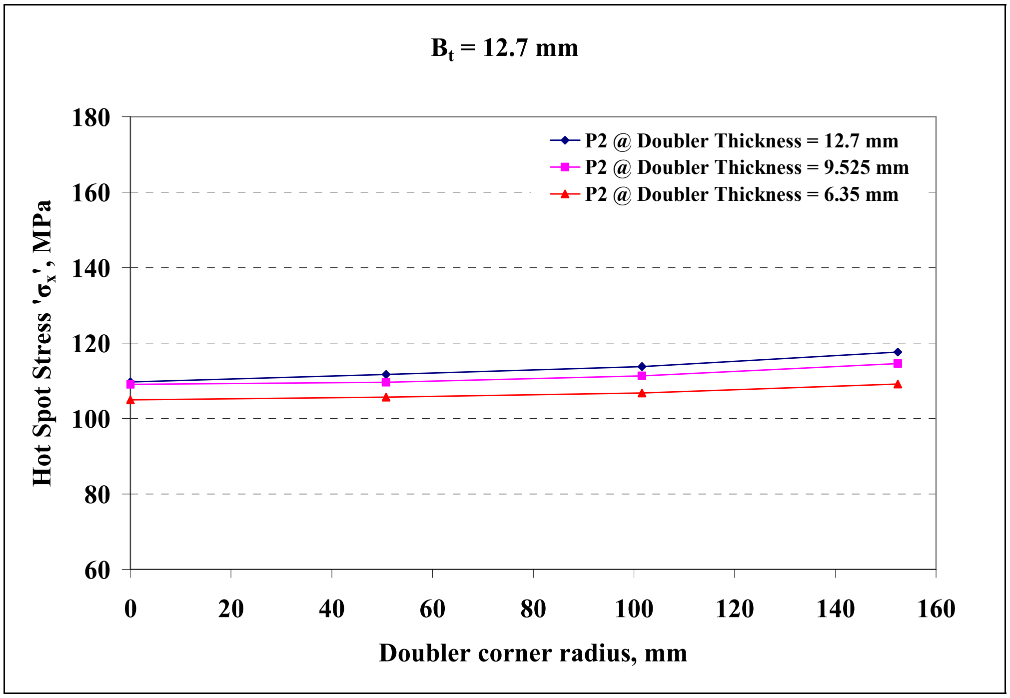


Figure 6.6: Effect of D_R on Hot Spot Stress at P2 @ B_t = 12.7 mm

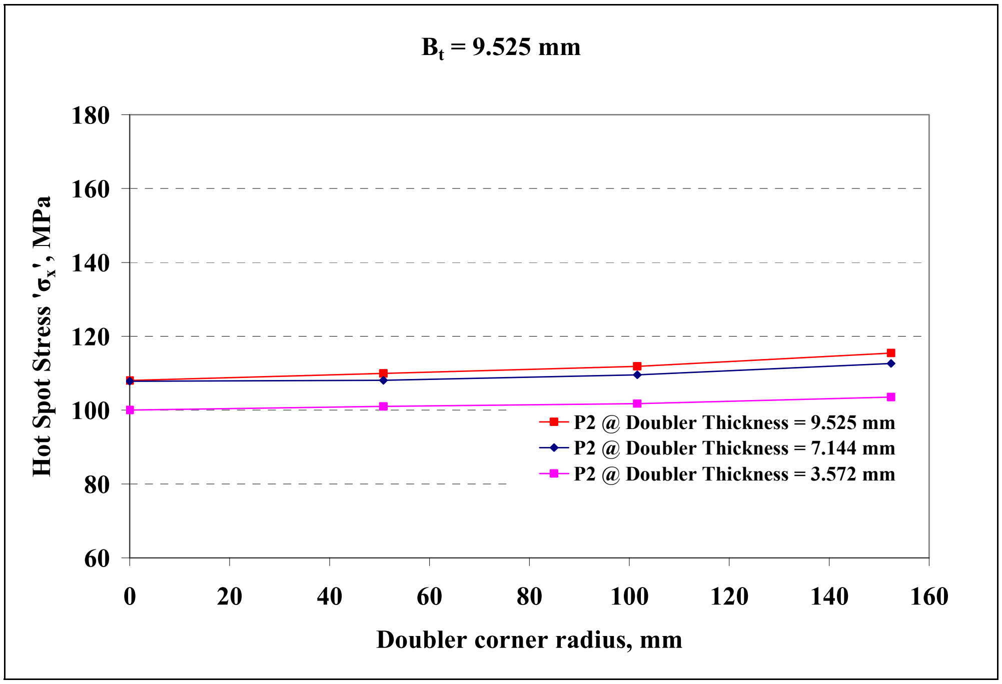


Figure 6.7: Effect of D_R on Hot Spot Stress at P2 @ B_t = 9.525 mm

6.1.6.2 Effect of Doubler Corner Radius on Fatigue Strength of Stiffened Panel at Location P1

As the corner radius of the doubler is increased, the sharpness of the corner decreases and one would expect the fatigue life of the corner to increase with the reduction in the local stress. Figures 6.8 and 6.9 illustrate the effect of corner radius on hot spot stress and fatigue strength of stiffened panel location P1. The reduction in hot spot stress at location P1 translates into an increase in fatigue life as shown in Figures 6.10 and 6.11. The changes in fatigue life resulting from changes in doubler corner radius are significant at the corner of the doubler plate.

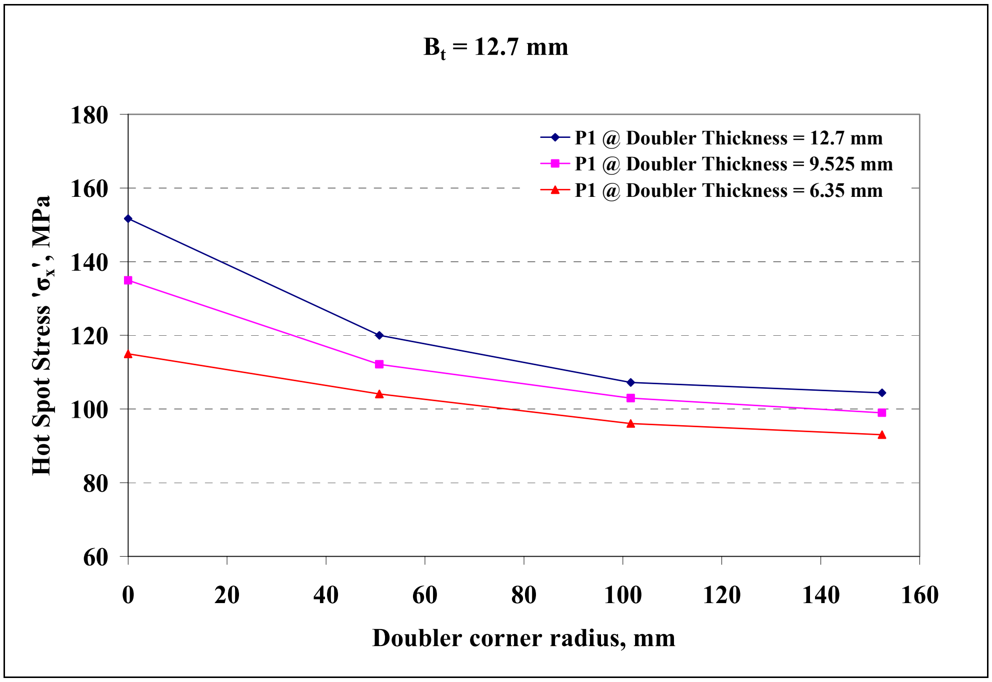


Figure 6.8: Effect of D_R on Hot Spot Stress at P1 @ B_t = 12.7 mm

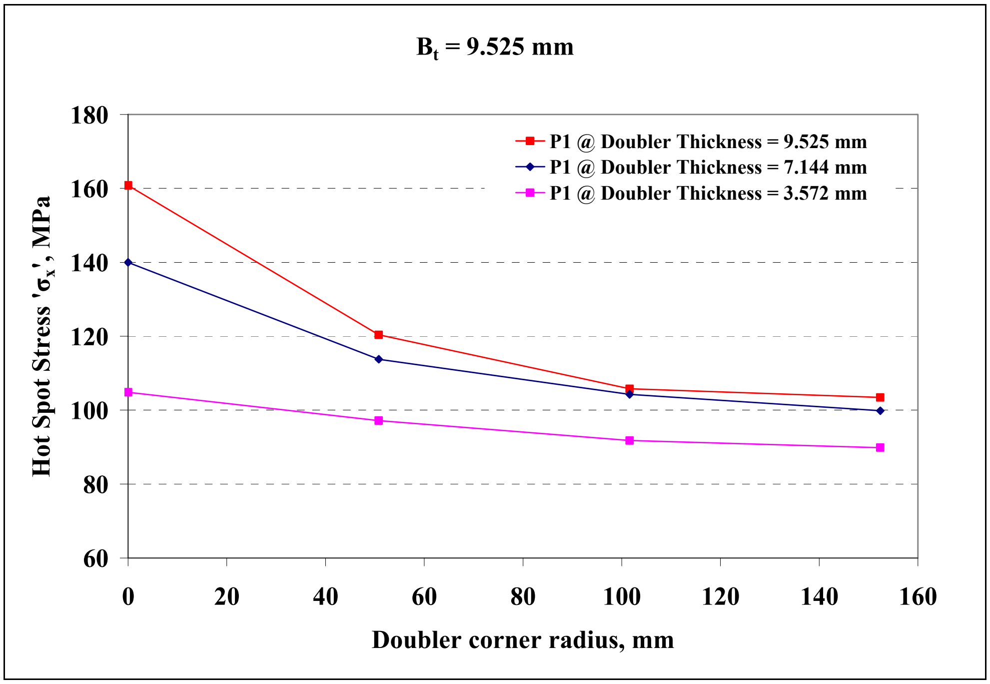


Figure 6.9: Effect of D_R on Hot Spot Stress at P1 @ B_t = 9.525 mm

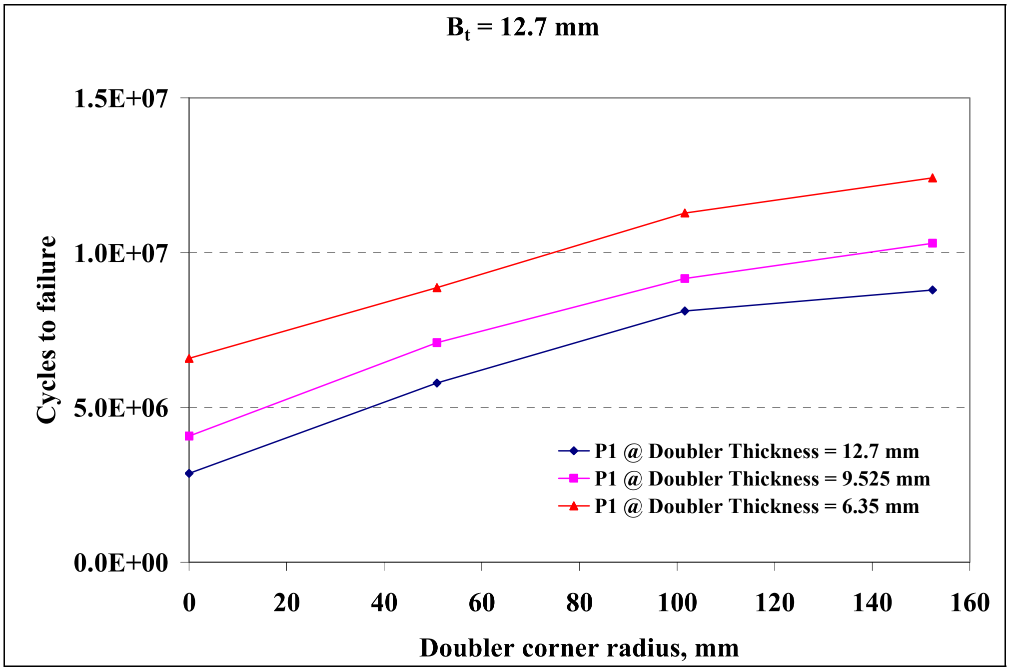


Figure 6.10: Effect of D_R on Fatigue Life at P1 @ B_t = 12.7 mm

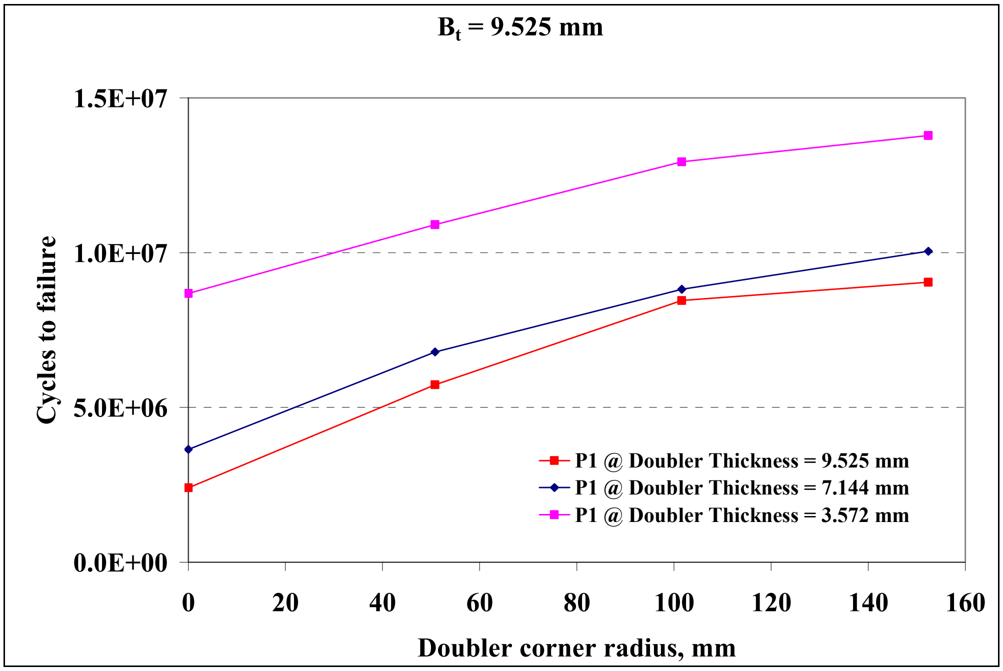


Figure 6.11: Effect of D_R on Fatigue Life at P1 @ B_t = 9.525 mm

6.1.6.3 Effect of Doubler Thickness on Fatigue Strength of Stiffened Panel at Location P1

For a constant corner radius as the thickness of the doubler is increased, the weld toe stress at location P1 increases. The rate at which the P1 location hot spot stress increases with doubler thickness is inversely related to the corner radius. In other words, the deleterious effect of thicker doubler plates is more pronounced for smaller corner radii as shown in Figures 6.12 and 6.13. The increase in local stress is maintained below 10% for all doubler thicknesses investigated as long as the corner radius of the doubler is greater than 50.8 mm.

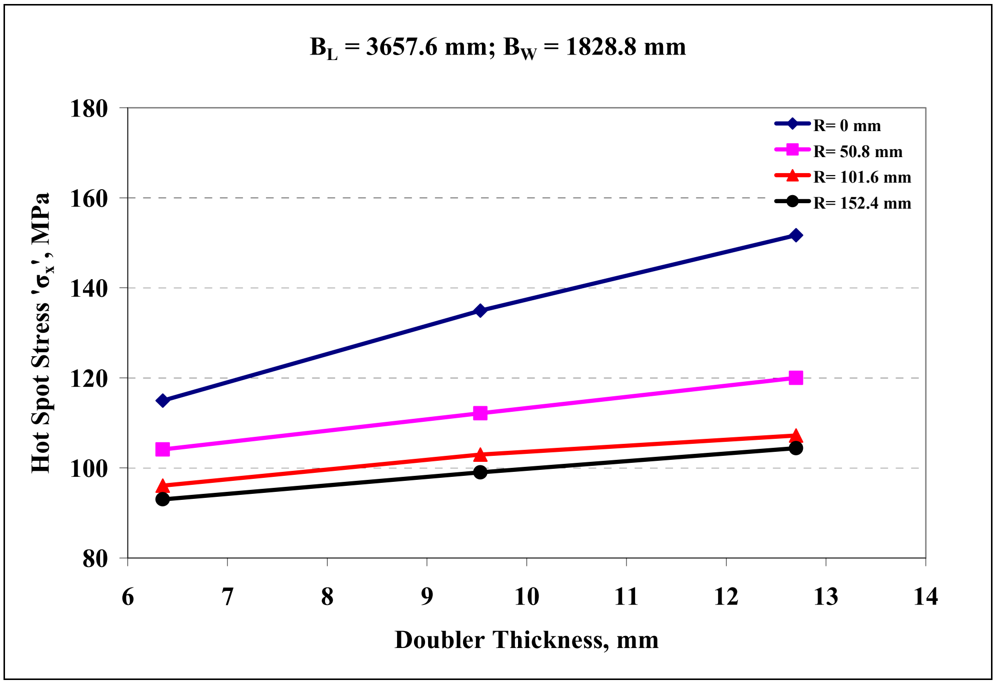


Figure 6.12: Effect of D_t on Hot Spot Stress at P1 @ B_t = 12.7 mm

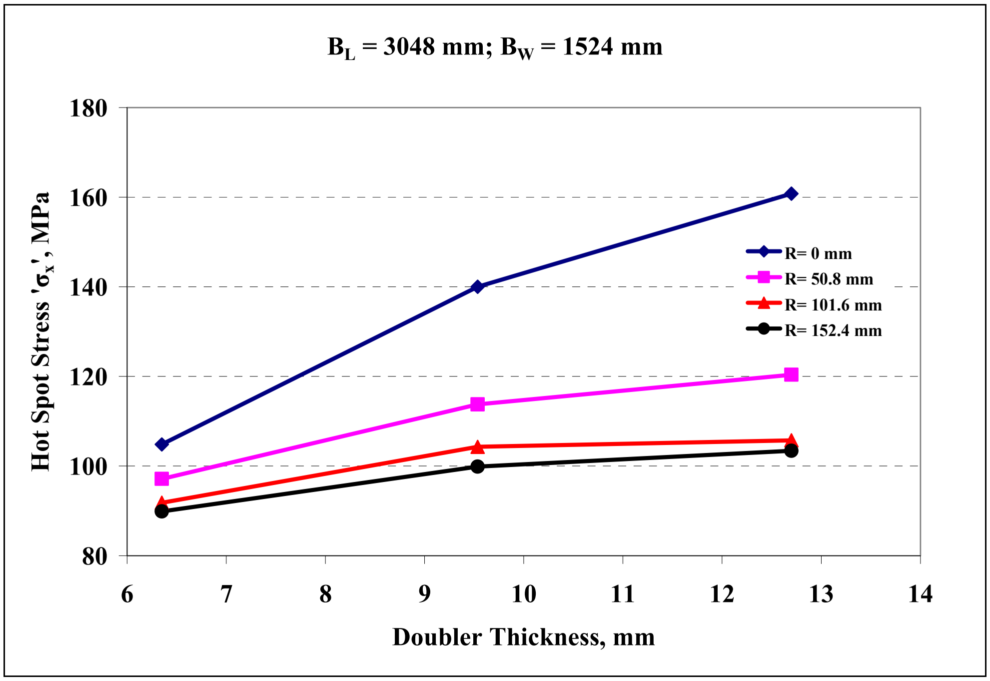


Figure 6.13: Effect of D_t on Hot Spot Stress @ B_t = 9.525 mm

6.1.7 Conclusions for Doubler Corner Radius

Based upon the analyses completed and the results presented, increasing doubler corner radius reduces stresses at the corners (location P1) of doubler plate, however, increasing doubler corner radius increases the stresses at the leading edge (location P2) of the doubler plate. In order to optimize a design, one would select the corner radius that produced similar fatigue lives (hot spot stresses) at the corner (location P1) and leading edge (location P2) of the doubler plate. Figures 6.14 to 6.19 illustrate the most "effective" corner radius for various doubler thicknesses.

6.1.7.1 Stiffened Panel Plate Thickness = 12.7 mm

The effective corner radius for the doubler decreases as doubler thickness decreases. For doubler thickness of 12.7 mm, 9.525 mm and 6.35 mm the effective corner radiuses are 79 mm, 62 mm and 42 mm, respectively (Figures 6.14 to 6.16).

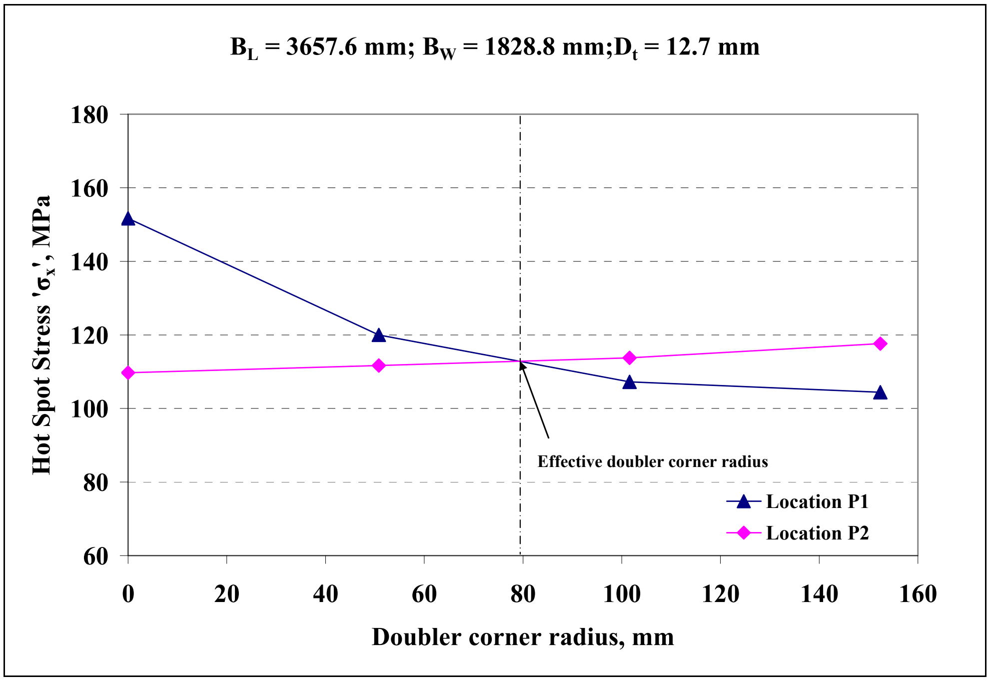


Figure 6.14: Doubler Thickness = 12.7 mm

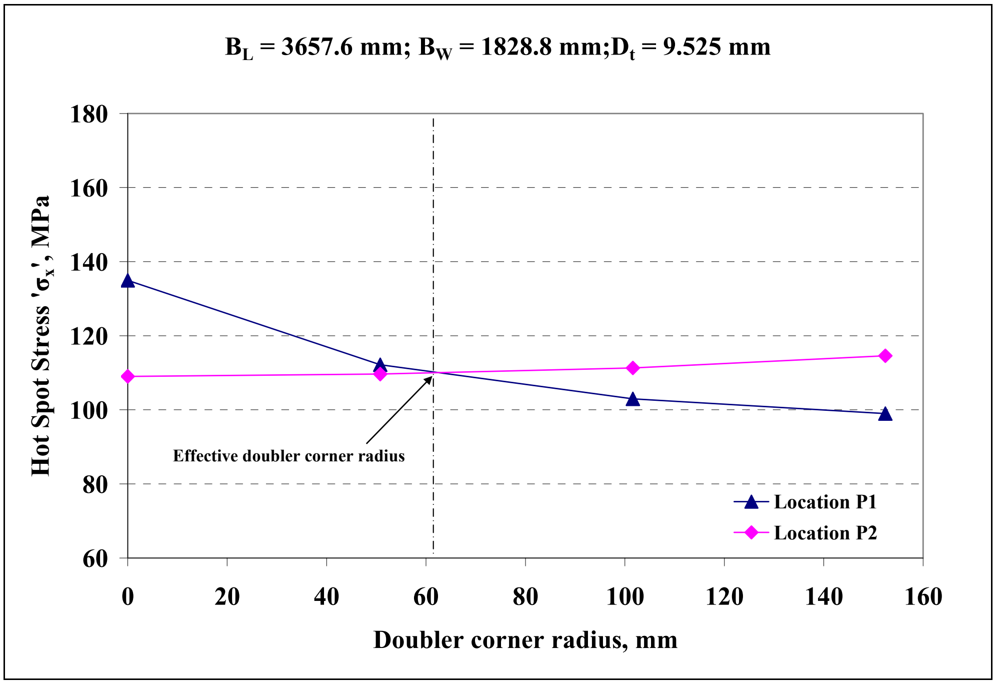


Figure 6.15: Doubler Thickness = 9.525 mm

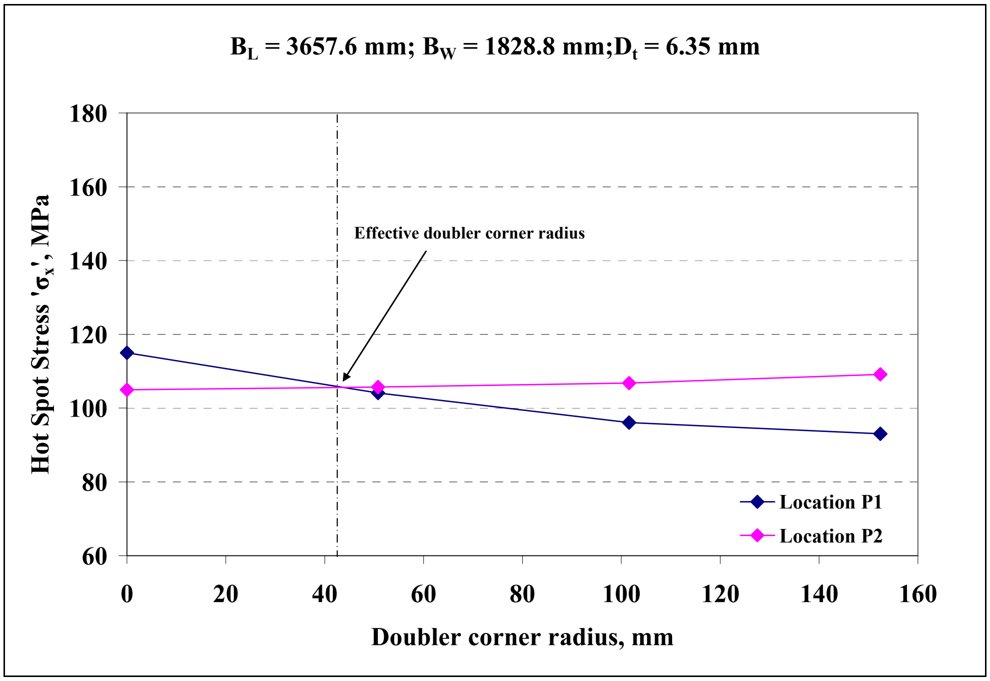


Figure 6.16: Doubler Thickness = 6.35 mm

6.1.7.2 Stiffened Panel Plate Thickness = 9.525 mm

The effective corner radius for the doubler decreases as doubler thickness decreases. For doubler thickness of 9.525 mm, 7.144 mm and 3.572 mm the effective corner radiuses are 84 mm, 78 mm and 30 mm respectively (Figures 6.17 to 6.19).

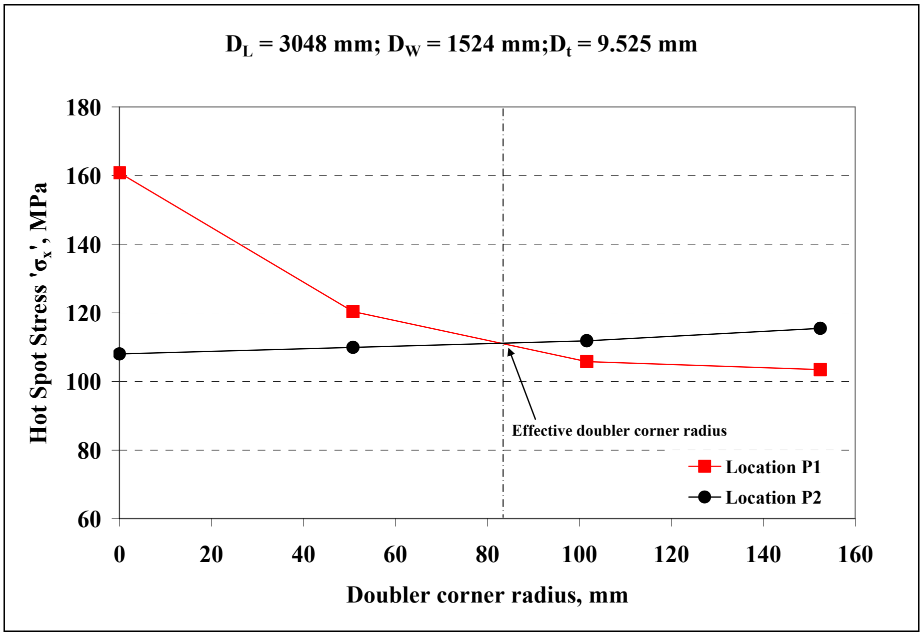


Figure 6.17: Doubler Thickness = 9.525 mm

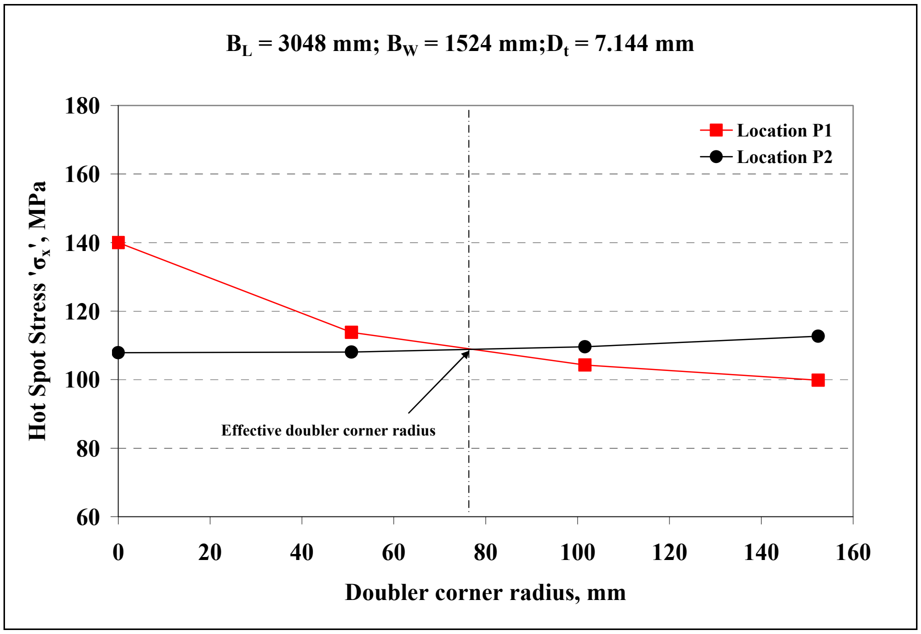


Figure 6.18: Doubler Thickness = 7.144 mm

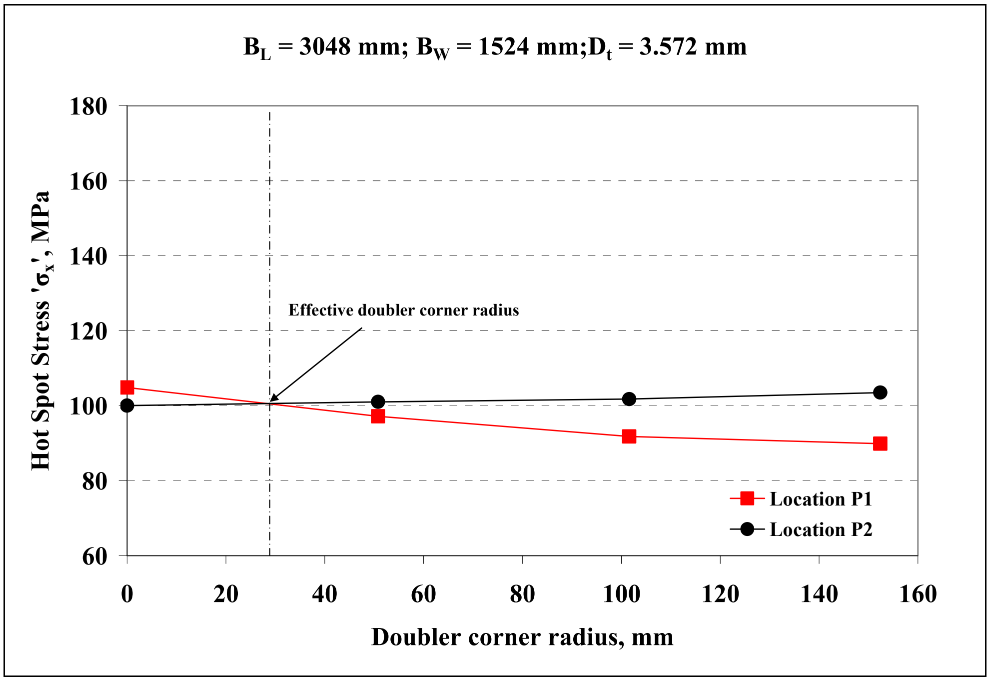


Figure 6.19: Doubler Thickness = 3.572 mm

6.1.8 Recommendations for Doubler Corner Radius

Based upon the results shown in Figures 6.14 through 6.19 it is suggested that the most appropriate doubler corner radius (D_R) can be defined based upon the ratio of the doubler thickness (D_t) and parent plate thickness (B_t). Table 6.2 summarizes the results from Figures 6.14 to 6.19. This relationship is defined in the equation shown in Figure 6.20 developed based upon a simple linear regression of the analysis results where R has units of mm. This equation may be used to define the most appropriate doubler corner radius for a range of plate thicknesses.

Table 6.2: Effect of Doubler to Base Plate Thickness Ratio

B_t, mm	D_t, mm	$D_{R\ optimal}$, mm	D_t/B_t
12.7	12.7	79	1
12.7	9.525	62	0.75
12.7	6.35	42	0.5
9.525	9.525	84	1
9.525	7.14	78	0.74961
9.525	3.572	30	0.37501

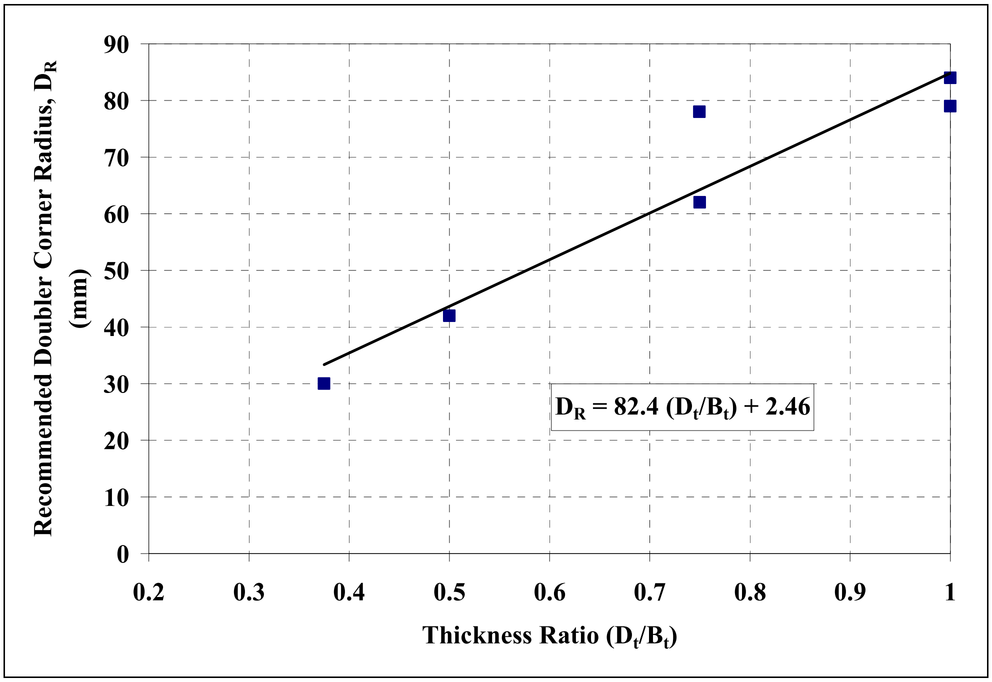


Figure 6.20: Recommended Doubler Corner Radius

If a constant corner radius is desired for all combinations of thickness, then it is suggested that a 75mm (3in) corner radius should be used.

6.2 Effect Of Doubler Size On Fatigue And Fracture Resistance

In order to demonstrate the effect of doubler size on fatigue and fracture strength of a corroded stiffened panel; two loading scenarios are considered:

1) Uniaxial Tensile Edge Loading
2) Lateral Loading

The following sections describe the analysis and results for this task. As described in the previous section, a hot spot stress approach is used to evaluate the performance of the corroded stiffened panels.

6.2.1 Finite Element Model

The stiffened panel, doubler plate, stiffeners and welds are modeled using ANSYS Solid186 (20 node brick) elements for static analysis. One element through thickness has been used. A refined mesh region with element size t x t x t in the vicinity of weld toe region is used to capture the stresses in the structure. Figures 6.21 and 6.22 illustrate the general geometry and element layout in the FE models used in this investigation along with the coordinate axes. It is noted that the doubler corner is not treated with the same level of detail as in Section 5.0. This treatment will promote a local stress concentration at the corner of the doubler plate. This local effect, however, does not influence the results presented in this section. The FE model boundary conditions are illustrated in Figure 6.23.

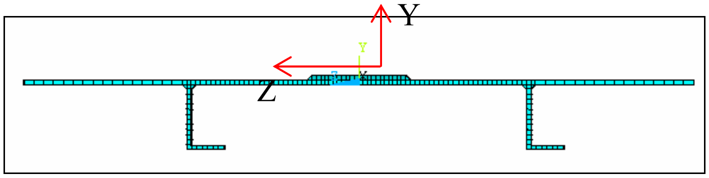


Figure 6.21: FE model of Stiffened Panel with Doubler

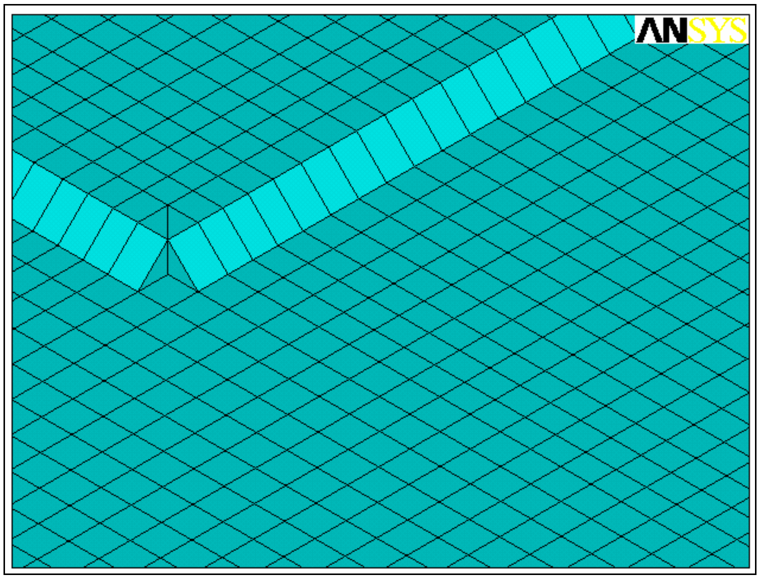


Figure 6.22: Solid Element Mesh Refinement

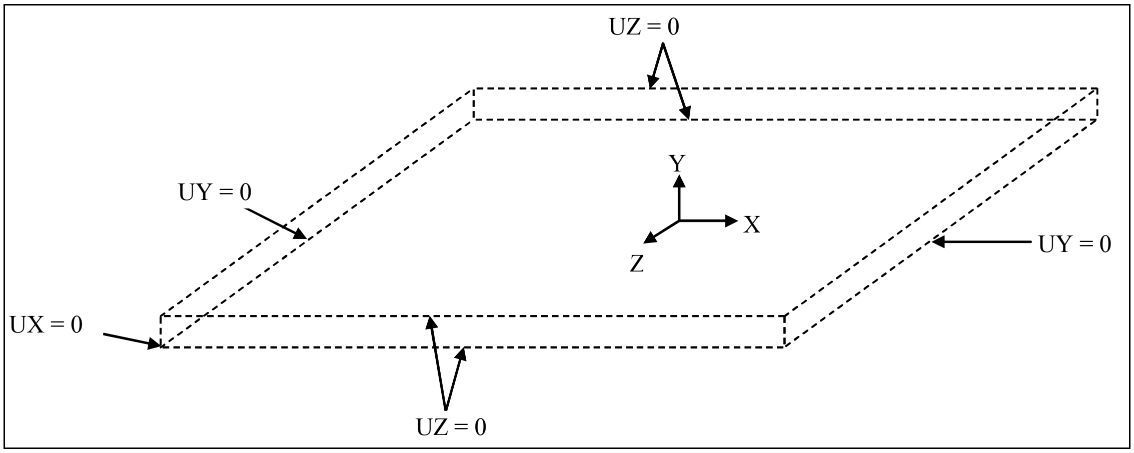


Figure 6.23: Boundary Conditions Applied to the FE Model

6.2.2 Geometry

In order to develop an understanding of the effects of welding a doubler plate to strengthen a corroded stiffened panel, a range of doubler plate thicknesses and corrosion aspect ratios were considered. The corrosion aspect ratio is defined as ratio of length of the corroded area to its width. For a constant corrosion width, aspect ratios of 4, 2, 1 and 0.5 were considered. The size of the corrosion feature determines the size of the doubler (i.e. the larger the corrosion area the larger the doubler). The doubler plate thickness is assumed to be 100%, 75% and 50% of the thickness of the stiffened panel. Table 6.3 illustrates the corroded stiffened panel geometry parameters that are assumed to be constant for the purpose of analysis. The results for various geometry variables investigated for the analysis under tensile and lateral loading scenarios are summarized in Tables 6.4 and 6.5, respectively.

Table 6.3: Constant Geometry Parameters for Doubler Plate Geometry Analysis

Stiffened Plate, mm			Stiffener ('L'shape)Size, mm			
Length, B_L	Width, B_W	Thick, B_t	Spacing 's'	Thickness, S_t	Height, S_L	Width, S_W
3657.6	1828.8	12.7	914.4	12.7	177.8	101.6

The analysis results suggested that for wide doublers, (e.g. Case 48 in Table 6.4) Figure 6.24, the doubler edge is close to panel edge and boundary effects may affect the results presented.

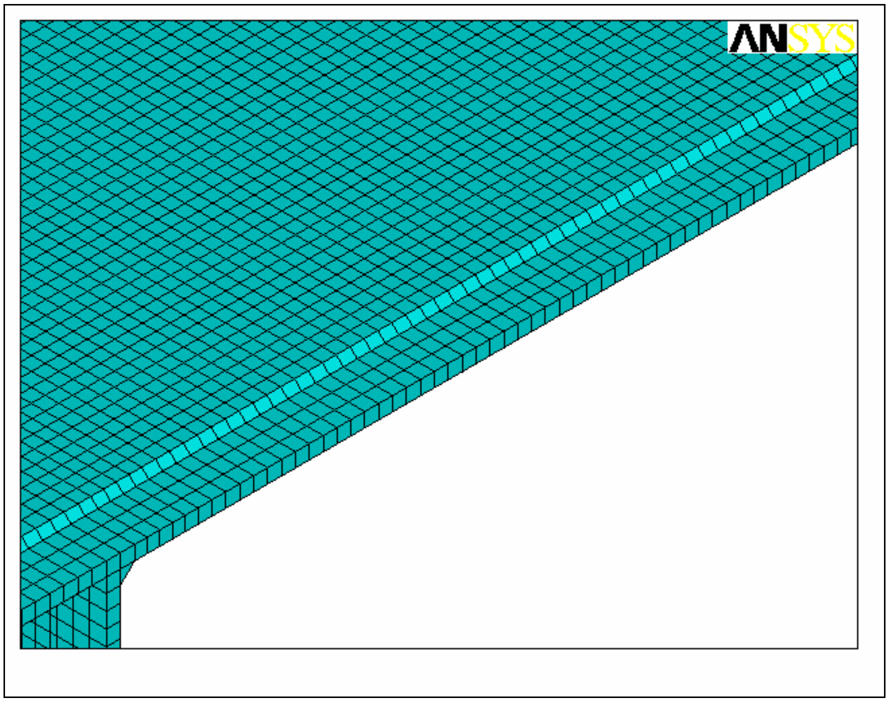


Figure 6.24: Load Case 48

6.2.3 Material Model

Due to the linear elastic nature of the investigation, the material behavior model used in this investigation was straightforward. A linear elastic material model based upon modulus of elasticity (E) of 207,000 MPa and Poisson’s ratio of 0.3 is used for the uncorroded and corroded stiffened panel FE models.

6.2.4 Hot Spot Stress Analysis

A hot spot stress approach is used to consider the expected relative fatigue performance of the stiffened panel. The hot spot stress approach considers the principal stress as affected by all stress concentration factors except that induced by the weld toe geometry. In these analyses, the hot spot stress is calculated at the weld toe location, P1 as illustrated in Figure 6.25. The stress at weld toe is linearly extrapolated from those at distance t/2 and 3t/2 from weld toe, where, 't' is the thickness of stiffened panel. Stress plots for few selected cases are shown in Appendix C (Figures C.13 through C.18).

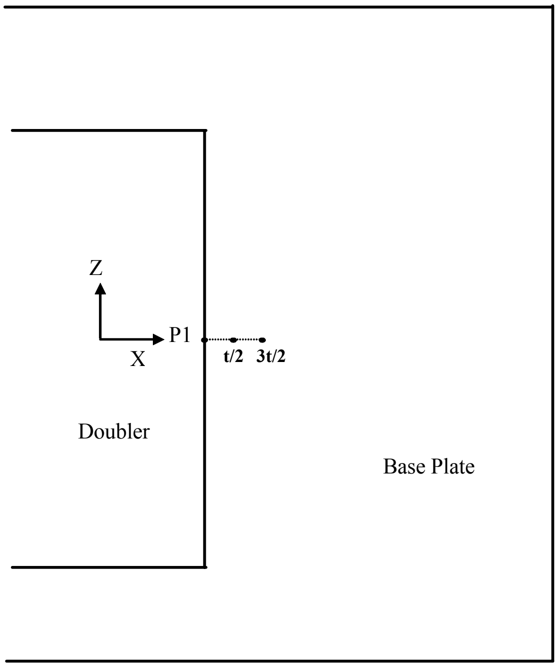


Figure 6.25: Hot Spot Stress Locations

6.2.5 Doubler Effectiveness

For a corroded stiffened panel the corroded area has the least strength and is most likely the site of crack initiation. For the doubler to be effective the average stress at the center of the corroded feature should be less than the hot spot stress at the weld toe .i.e.

$$\frac{\sigma_{\mathrm{X\,Top}} + \sigma_{\mathrm{X\,Bottom}}}{2} < \text{Hot Spot Stress '}\sigma_{\mathrm{X}}\text{' at Weld Toe}$$

where $\boldsymbol{\sigma}_{\mathbf{X}\ \mathrm{Top}}$ and $\boldsymbol{\sigma}_{\mathbf{X}\ \mathrm{Bottom}}$ are the principal stress magnitudes at the top and bottom surface of the stiffened panel plate at the center of the corrosion feature.

The location of crack initiation considered in this investigation is the weld toe. Figure 6.26 illustrates the locations for data collection from the FE models.

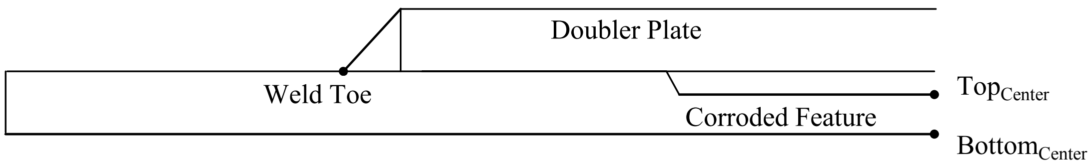


Figure 6.26: Effectiveness of Doubler

6.2.6 Loading

The stiffened panel is subjected to a uni-axial tensile edge loading (x-direction) of 75.84 Mpa and lateral pressure (y-direction) of 0.028 Mpa. Since the nature of the analysis is linear, notional or unit loads are usually sufficient.

6.2.7 Tensile Loading Results

The results for hot spot stress analysis for various geometries are summarized in Table 6.4. From the results presented in Table 6.4, we can see that the fatigue strength of the corroded stiffened panel subjected to a uni-axial tensile edge loading is enhanced by the use of doubler plate considering the potential for fatigue at the weld toe according to the definition outlined in Section 6.2.5.

Table 6.4: Hot Spot Stress Summary for Tensile Loading

	Doubler Thickness D_t	Corroded Feature, mm		Doubler to corrosion edge distance	Hot Spot Stress 'SX'	Stress 'SX' in the Center of the Corroded Feature, MPa			Effectiveness of Doubler (E–Effective,
Case No.	mm	Width C_W	Length C_L	mm	MPa	Top	Bottom	Average	NE–Not Effec.)
1	12.7	152.4	76.2	25.4	77.84	66.83	82.29	74.56	E
2	12.7	152.4	76.2	50.8	80.17	72.84	76.89	74.87	E
3	12.7	152.4	76.2	101.6	85.09	78.31	70.75	74.53	E
4	12.7	152.4	76.2	254	96.71	82.82	54.79	68.81	E
5	12.7	152.4	152.4	25.4	84.74	59.84	84.66	72.25	E
6	12.7	152.4	152.4	50.8	86.32	63.17	81.26	72.21	E
7	12.7	152.4	152.4	101.6	90.32	66.98	75.8	71.39	E
8	12.7	152.4	152.4	254	99.38	70.89	59.15	65.02	E
9	12.7	152.4	304.8	25.4	96.14	56.93	82.21	69.57	E
10	12.7	152.4	304.8	50.8	96.75	57.71	80.32	69.02	E
11	12.7	152.4	304.8	101.6	99.08	59.6	75.31	67.45	E
12	12.7	152.4	304.8	254	103.09	62.83	57.61	60.22	E
13	12.7	152.4	609.6	25.4	111.31	58.31	73.98	66.15	E
14	12.7	152.4	609.6	50.8	110.58	58.06	72.16	65.11	E
15	12.7	152.4	609.6	101.6	110.08	58.23	67.73	62.98	E
16	12.7	152.4	609.6	254	107.08	59.77	52.71	56.24	E
17	9.525	457.2	228.6	25.4	83.56	60.11	86.49	73.3	E
18	9.525	457.2	228.6	50.8	85.94	63.81	81.78	72.79	E
19	9.525	457.2	228.6	101.6	90.39	69.66	73.09	71.37	E
20	9.525	457.2	228.6	254	99.88	79.87	51.9	65.88	E
21	9.525	457.2	457.2	25.4	95.6	59.86	77.68	68.77	E
22	9.525	457.2	457.2	50.8	96.61	61.74	74.28	68.01	E
23	9.525	457.2	457.2	101.6	98.37	65.33	67.34	66.34	E
24	9.525	457.2	457.2	254	103.01	70.2	52.91	61.55	E
25	9.525	457.2	914.4	25.4	105.83	63.04	65.16	64.1	E
26	9.525	457.2	914.4	50.8	105.28	63.5	63.14	63.32	E
27	9.525	457.2	914.4	101.6	104.68	64.22	59.55	61.89	E
28	9.525	457.2	914.4	254	105.94	62.29	53.26	57.78	E
29	9.525	457.2	1828.8	25.4	109.01	62.11	61.28	61.69	E
30	9.525	457.2	1828.8	50.8	108.2	61.53	60.37	60.95	E
31	9.525	457.2	1828.8	101.6	107.21	60.44	58.74	59.59	E
32	9.525	457.2	1828.8	254	107.77	56.84	54.1	55.47	E
33	6.35	762	381	25.4	89.15	61.77	81.61	71.69	E
34	6.35	762	381	50.8	90.89	64.79	77.4	71.09	E
35	6.35	762	381	101.6	93.68	70.06	69.68	69.87	E
36	6.35	762	381	254	98.89	80.19	52.89	66.54	E
37	6.35	762	762	25.4	97.12	67.57	67.45	67.51	E
38	6.35	762	762	50.8	97.54	68.45	65.51	66.98	E
39	6.35	762	762	101.6	98.42	69.34	62.59	65.97	E
40	6.35	762	762	254	101.17	69.5	56.93	63.21	E

Table 6.4: Hot Spot Stress Summary for Tensile Loading (cont.)

Case No.	Doubler Thickness D_t mm	Corroded Feature, mm		Doubler to corrosion edge distance mm	Hot Spot Stress 'SX' MPa	Stress 'SX' in the Center of the Corroded Feature, MPa			Effectiveness of Doubler (E–Effective, NE–Not Effec.)
		Width C_W	Length C_L			Top	Bottom	Average	
41	6.35	762	1524	25.4	100.65	67.59	63.02	65.3	E
42	6.35	762	1524	50.8	100.7	67.07	62.37	64.72	E
43	6.35	762	1524	101.6	101.08	65.68	61.42	63.55	E
44	6.35	762	1524	254	103.22	62.27	58.38	60.32	E
45	6.35	762	3048	25.4	103.61	64.65	63.73	64.19	E
46	6.35	762	3048	50.8	103.32	64.13	62.92	63.52	E
47	6.35	762	3048	101.6	101.88	62.91	61.49	62.2	E
48	6.35	762	3048	254	76.14	60.15	56.95	58.55	E
49	12.7	762	381	25.4	88.15	56.23	81.84	69.04	E
50	12.7	762	381	101.6	93.97	62.06	68.91	65.48	E
51	12.7	762	381	254	100.57	70.47	48.47	59.47	E
52	12.7	762	762	25.4	100.62	59.47	63.11	61.29	E
53	12.7	762	762	101.6	101.99	60.84	56.06	58.45	E
54	12.7	762	762	254	104.35	60.74	47.28	54.01	E
55	12.7	762	1524	25.4	106.72	58.46	54.47	56.47	E
56	12.7	762	1524	101.6	106.16	56.09	51.88	53.99	E
57	12.7	762	1524	254	106.99	51.74	47.46	49.6	E
58	9.525	152.4	76.2	25.4	79.2	67.65	82.67	75.16	E
59	9.525	152.4	76.2	50.8	81.85	73.49	77.41	75.45	E
60	9.525	152.4	76.2	101.6	87.08	79.04	71.22	75.13	E
61	9.525	152.4	152.4	25.4	85.74	61.19	84.15	72.67	E
62	9.525	152.4	152.4	50.8	87.55	64.41	80.92	72.67	E
63	9.525	152.4	152.4	101.6	91.73	68.22	75.67	71.95	E
64	9.525	152.4	304.8	25.4	95.98	58.96	80.94	69.95	E
65	9.525	152.4	304.8	50.8	96.91	59.76	79.14	69.45	E
66	9.525	152.4	304.8	101.6	99.46	61.69	74.46	68.08	E
67	9.525	152.4	609.6	25.4	107.59	60.99	73.14	67.06	E
68	9.525	152.4	609.6	50.8	107.62	60.76	71.5	66.13	E
69	9.525	152.4	609.6	101.6	108.04	61.15	67.48	64.31	E

6.2.7.1 Effect of Doubler Edge Distance and Corrosion Aspect Ratio on Hot Spot Stress

The results presented in Figures 6.27 through 6.31 illustrate that for a constant corrosion aspect ratio (ratio of length of the corroded area to its width) as the size of the doubler increases, hot spot stress increases. These figures also indicate that for higher corrosion aspect ratios ($C_L > C_W$), the doubler plate edge does not have a significant effect on weld toe stresses. Therefore the doubler plate to corrosion feature edge distance can be any value. However, care should be taken to minimize the size of the doubler plate because large doubler plates will need slot welds to ensure stability. The results also indicate that as the corrosion feature aspect ratio increases the hot spot stress increases. At doubler to corrosion edge distance of 254 mm, the corrosion aspect ratio has less of an effect on the weld toe stress.

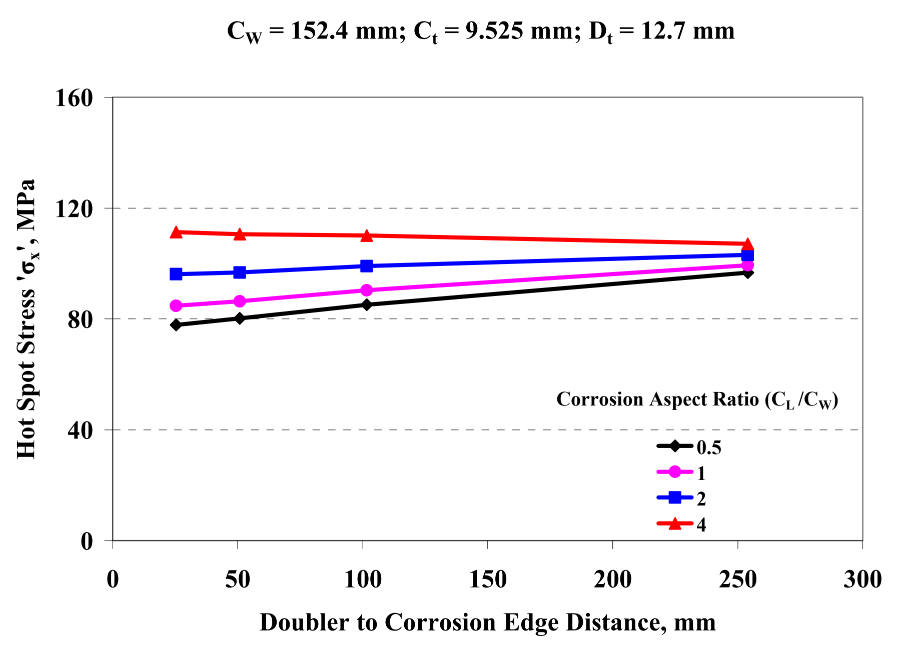


Figure 6.27: Effect of Doubler Size for D_t = 12.7 mm and C_W = 152.4 mm

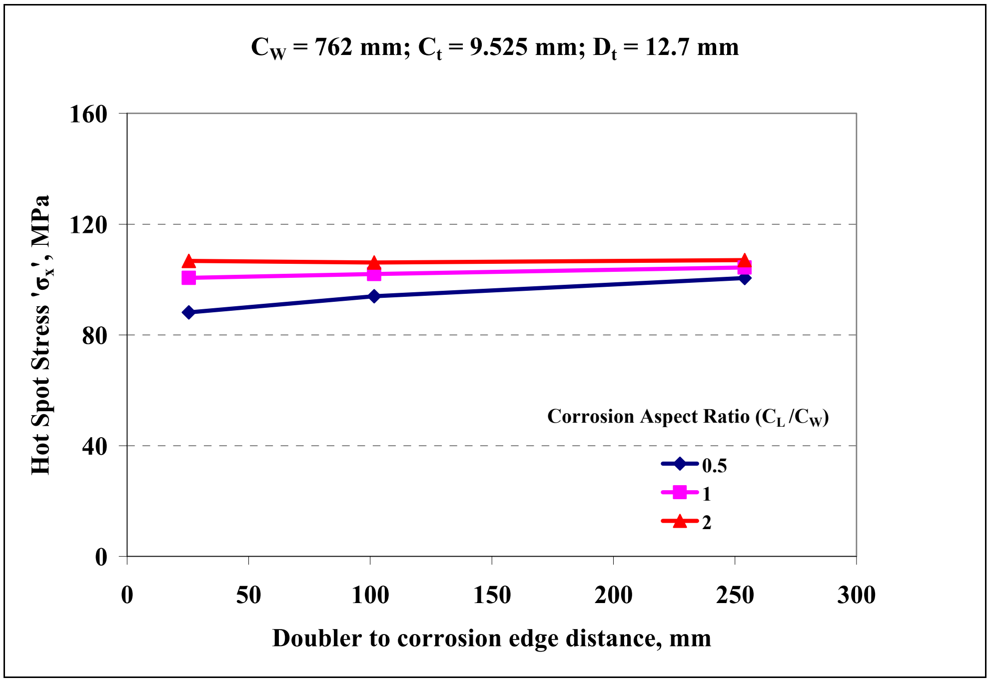


Figure 6.28: Effect of Doubler Size for D_t = 12.7 mm and C_W = 762 mm

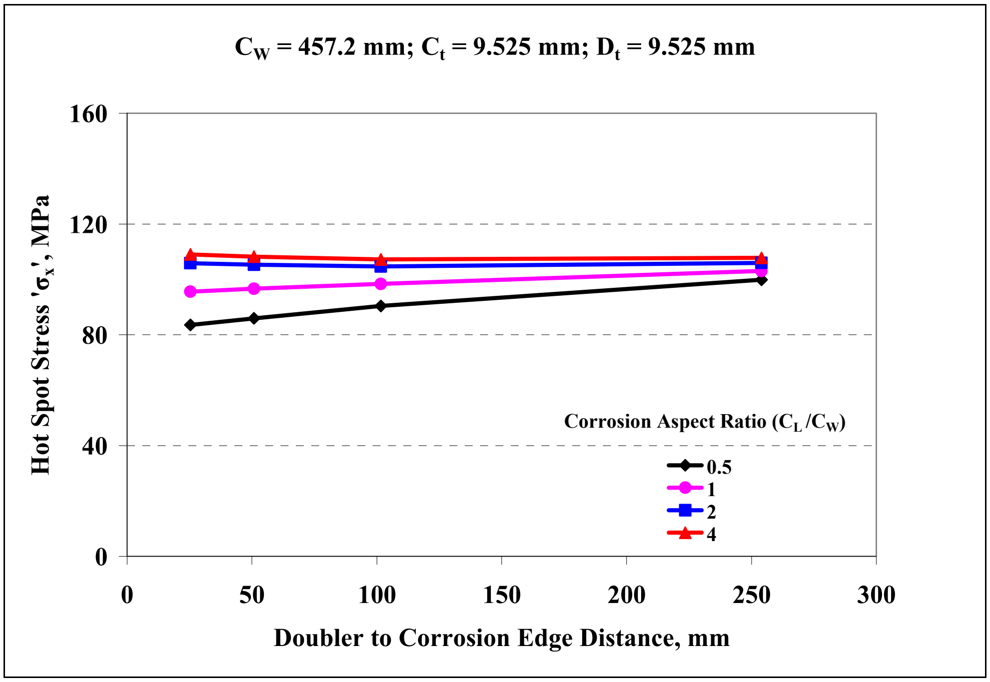


Figure 6.29: Effect of Doubler Size for D_t = 9.525 mm and C_W = 457.2 mm

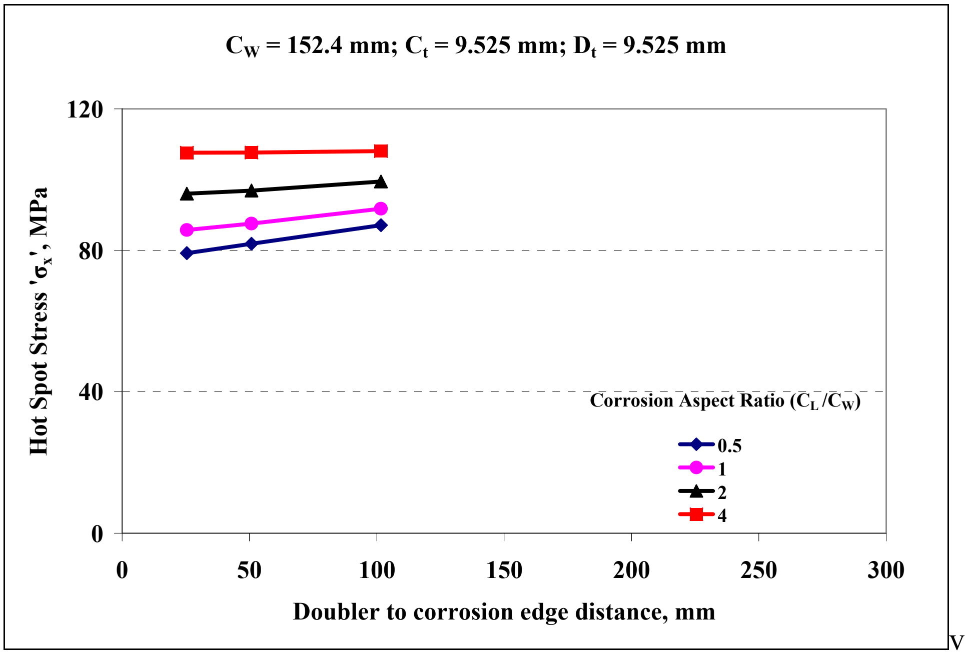


Figure 6.30: Effect of Doubler Size for D_t = 9.525 mm and Cw = 152.4 mm

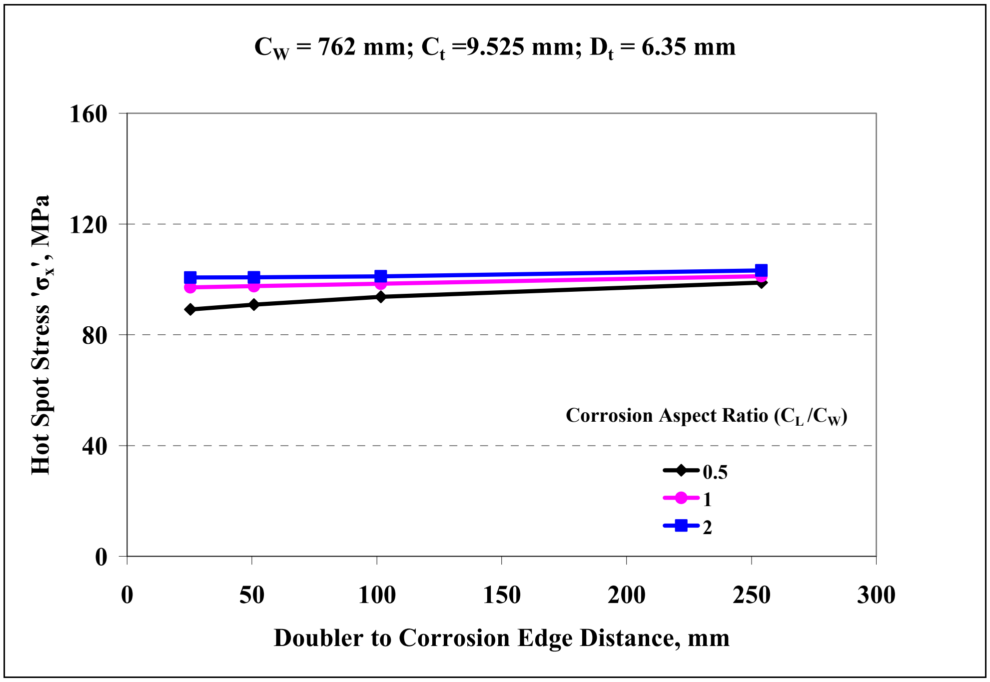


Figure 6.31: Effect of Doubler Size for D_t = 6.35 mm and C_W = 762 mm

For a constant doubler thickness and edge distance, a larger corrosion feature would increase weld toe hot spot stresses and thus lower the repaired stiffened panel fatigue strength as illustrated in Figure 6.32.

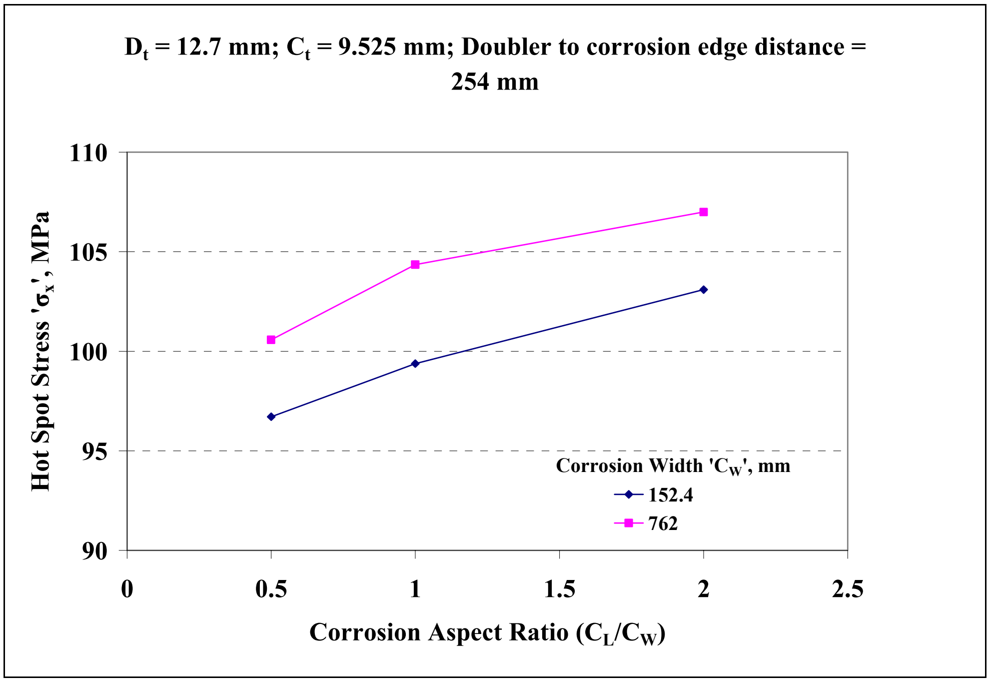


Figure 6.32: Effect of Corrosion on Hot Spot Stress

6.2.7.2 Effect of Doubler Thickness Factor

To study the effect of corrosion on strength of corroded stiffened panel, the 'Doubler Thickness Factor' introduced previously in section 2.5.4 was used.

Figures 6.33 and 6.34 illustrate the effect of doubler thickness factor on hot spot stress for a doubler plate edge distance of 50.8 mm. Figure 6.33 (C_w = 762 mm) shows that the hot spot stress increases with the doubler thickness factor where as Figure 6.34 (C_w = 152.4 mm) illustrates that the hot spot stress decreases with the doubler thickness factor. This indicates that as the width of the corroded feature increases i.e. edge of corrosion gets closer to the stiffener; a thinner doubler would generate lower weld toe stress.

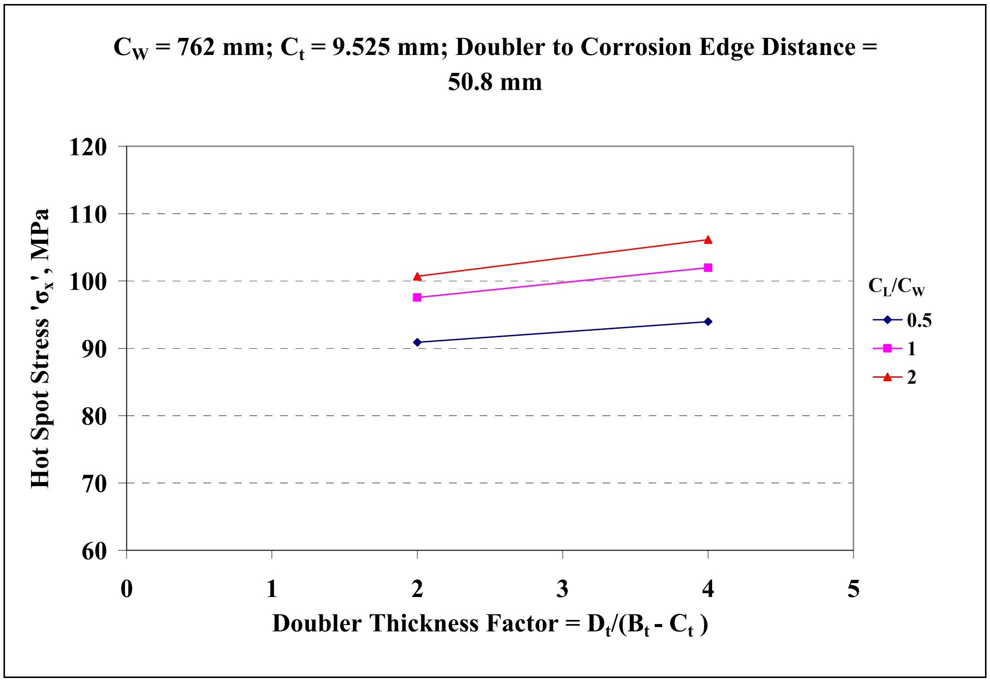


Figure 6.33: Effect of Doubler Thickness Factor for C_W = 762 mm

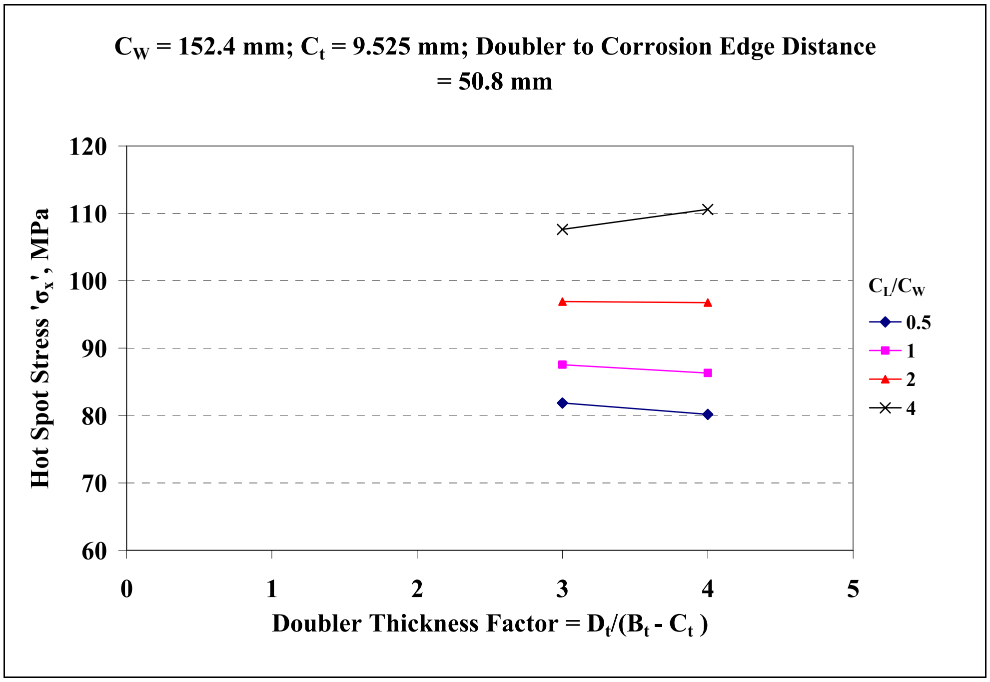


Figure 6.34: Effect of Doubler Thickness Factor for C_W = 152.4 mm

6.2.8 Lateral Loading Results

The results for hot spot stress analysis of a corroded stiffened panel subjected to lateral pressure for various doubler and corrosion geometries are summarized in Table 6.5.

For Cases 1 to 3 and 48 in Table 6.5, it can be seen that as the doubler edge distance increases, average stress in center of the corroded region is less than that at the weld toe. In these cases the doubler repair would be considered ineffective.

6.2.8.1 Effect of Doubler Edge Distance and Corrosion Aspect Ratio on Hot Spot Stress for C_W = 152.4 mm

For a corrosion width of 16% of the stiffener spacing, as the corrosion aspect ratio increases, the hot spot stress increases. As the doubler to corrosion edge distance approaches 254 mm, the effect of corrosion aspect ratio diminishes (Figure 6.35 and 6.36). At doubler to corrosion edge distance of 254 mm, the corrosion aspect ratio has less effect on the weld toe stress.

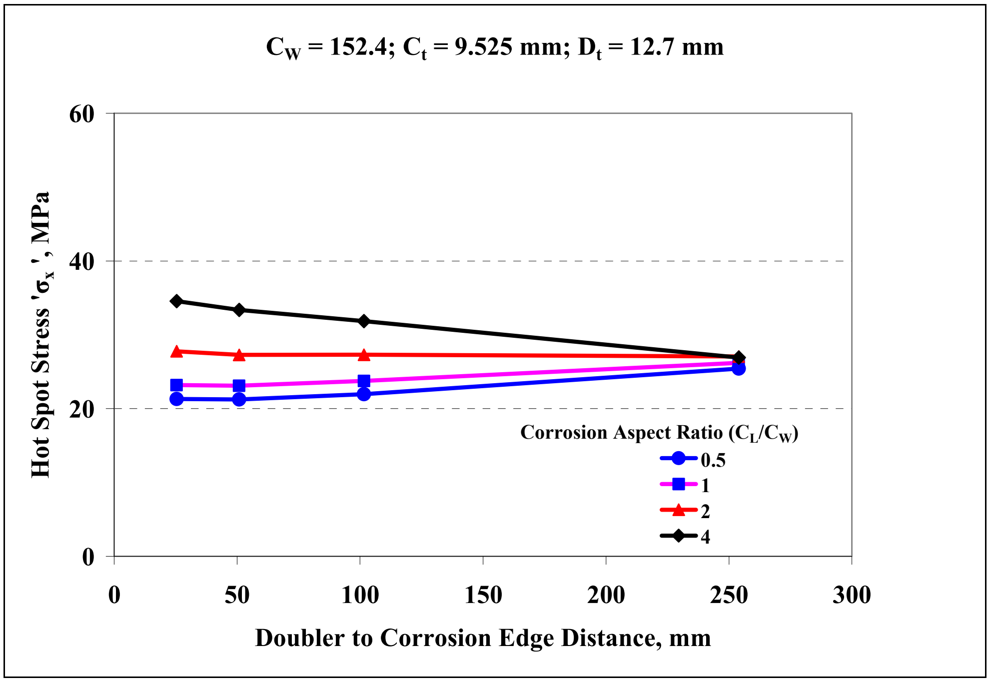


Figure 6.35: Effect of Doubler Size for D_t = 12.7 mm

Table 6.5: Hot Spot Stress Summary for Lateral Loading

	Doubler Thickness D_t	Corroded Feature, mm		Doubler to corrosion edge distance	Hot Spot Stress 'SX'	Stress 'SX' in the Center of the Corroded Feature, MPa			Effectiveness of Doubler (E–Effective,
Case No.	mm	Width C_W	Length C_L	mm	MPa	Top	Bottom	Average	NE–Not Effec.)
1	12.7	152.4	76.2	25.4	21.3	22.6	25.1	23.85	NE
2	12.7	152.4	76.2	50.8	21.24	24.78	22.63	23.7	NE
3	12.7	152.4	76.2	101.6	21.94	27.35	18.81	23.08	NE
4	12.7	152.4	76.2	254	25.42	34.48	1.9	18.19	E
5	12.7	152.4	152.4	25.4	23.18	19.88	24.8	22.34	E
6	12.7	152.4	152.4	50.8	23.08	21.22	23.22	22.22	E
7	12.7	152.4	152.4	101.6	23.73	23.41	19.68	21.55	E
8	12.7	152.4	152.4	254	26.18	30.41	2.16	16.29	E
9	12.7	152.4	304.8	25.4	27.76	17.51	22.55	20.03	E
10	12.7	152.4	304.8	50.8	27.27	18.18	21.77	19.97	E
11	12.7	152.4	304.8	101.6	27.3	20.08	18.59	19.33	E
12	12.7	152.4	304.8	254	27.05	27.62	0.52	14.07	E
13	12.7	152.4	609.6	25.4	34.56	17.87	17.19	17.53	E
14	12.7	152.4	609.6	50.8	33.37	17.97	16.51	17.24	E
15	12.7	152.4	609.6	101.6	31.85	18.91	13.91	16.41	E
16	12.7	152.4	609.6	254	26.91	25.98	-1.56	12.21	E
17	9.525	457.2	228.6	25.4	26.38	23.45	19.16	21.31	E
18	9.525	457.2	228.6	50.8	27	25.37	15.99	20.68	E
19	9.525	457.2	228.6	101.6	28.25	29.11	9.11	19.11	E
20	9.525	457.2	228.6	254	26.44	40.65	-11.7	14.48	E
21	9.525	457.2	457.2	25.4	29.88	25.27	13.01	19.14	E
22	9.525	457.2	457.2	50.8	30.17	26.68	10.21	18.45	E
23	9.525	457.2	457.2	101.6	30.28	30.02	3.67	16.85	E
24	9.525	457.2	457.2	254	25.83	39.25	-13.59	12.83	E
25	9.525	457.2	914.4	25.4	32.66	25.23	7.11	16.17	E
26	9.525	457.2	914.4	50.8	31.9	26.27	5.14	15.71	E
27	9.525	457.2	914.4	101.6	30.22	28.69	0.82	14.76	E
28	9.525	457.2	914.4	254	23.33	35.21	-10.63	12.29	E
29	9.525	457.2	1828.8	25.4	27.25	24.58	4.15	14.36	E
30	9.525	457.2	1828.8	50.8	26.06	24.92	3.22	14.07	E
31	9.525	457.2	1828.8	101.6	23.72	25.94	1.19	13.56	E
32	9.525	457.2	1828.8	254	17.11	30.76	-5.89	12.43	E
33	6.35	762	381	25.4	32.54	31.41	3.12	17.27	E
34	6.35	762	381	50.8	31.81	33.64	-0.16	16.74	E
35	6.35	762	381	101.6	30.72	37.74	-6	15.87	E
36	6.35	762	381	254	27.82	45.49	-16.4	14.54	E
37	6.35	762	762	25.4	31.61	40.46	-8.31	16.07	E
38	6.35	762	762	50.8	30.35	41.77	-10.27	15.75	E
39	6.35	762	762	101.6	28.57	43.27	-12.84	15.21	E
40	6.35	762	762	254	25.35	44.1	-15.06	14.52	E

Table 6.5: Hot Spot Stress Summary for Lateral Loading (cont.)

	Doubler Thickness D_t	Corroded Feature, mm		Doubler to corrosion edge distance	Hot Spot Stress 'SX'	Stress 'SX' in the Center of the Corroded Feature, MPa			Effectiveness of Doubler (E–Effective,
Case No.	mm	Width C_W	Length C_L	mm	MPa	Top	Bottom	Average	NE–Not Effec.)
41	6.35	762	1524	25.4	26.76	37.79	-5.15	16.32	E
42	6.35	762	1524	50.8	25.24	38.53	-6.15	16.19	E
43	6.35	762	1524	101.6	23.33	39.1	-7.35	15.88	E
44	6.35	762	1524	254	20.51	39.48	-8.74	15.37	E
45	6.35	762	3048	25.4	21.02	35.24	-2.68	16.28	E
46	6.35	762	3048	50.8	20.03	35.9	-3.47	16.22	E
47	6.35	762	3048	101.6	18.98	36.79	-4.63	16.08	E
48	6.35	762	3048	254	10.01	39.08	-6.78	16.15	NE
49	12.7	762	381	25.4	21.71	28.46	7.98	18.22	E
50	12.7	762	381	101.6	20.69	33.75	-3.59	15.08	E
51	12.7	762	381	254	18.69	42.04	-19.73	11.16	E
52	12.7	762	762	25.4	23.91	40.14	-11.28	14.43	E
53	12.7	762	762	101.6	20.76	42.79	-18.36	12.21	E
54	12.7	762	762	254	17.16	42.32	-22.4	9.96	E
55	12.7	762	1524	25.4	20.2	34.5	-9.31	12.6	E
56	12.7	762	1524	101.6	16.09	35.99	-12.93	11.53	E
57	12.7	762	1524	254	12.93	35.77	-15.1	10.33	E
58	9.525	152.4	76.2	25.4	26.18	22.83	23.33	23.08	E
59	9.525	152.4	76.2	50.8	26.41	25	20.98	22.99	E
60	9.525	152.4	76.2	101.6	27.46	27.6	17.28	22.44	E
61	9.525	152.4	152.4	25.4	27.9	20.2	23.21	21.71	E
62	9.525	152.4	152.4	50.8	28.09	21.63	21.59	21.61	E
63	9.525	152.4	152.4	101.6	29.03	23.91	18.07	20.99	E
64	9.525	152.4	304.8	25.4	31.93	18.3	20.94	19.62	E
65	9.525	152.4	304.8	50.8	31.76	19.04	20.11	19.58	E
66	9.525	152.4	304.8	101.6	32.08	21.04	16.96	19	E
67	9.525	152.4	609.6	25.4	36.99	19.33	15.66	17.49	E
68	9.525	152.4	609.6	50.8	36.29	19.46	15.03	17.24	E
69	9.525	152.4	609.6	101.6	35.3	20.57	12.59	16.58	E

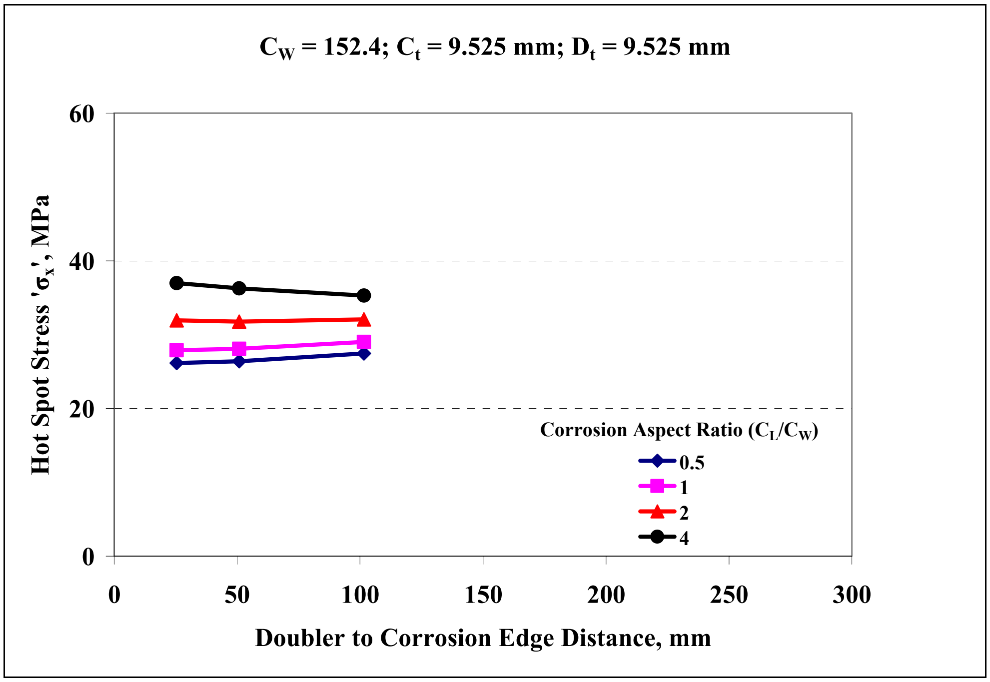


Figure 6.36: Effect of Doubler Size for D_t = 9.525 mm and C_W = 152.4 mm

6.2.8.2 Effect of Doubler Edge Distance and Corrosion Aspect Ratio on Hot Spot Stress for CW = 457.2 mm

At corrosion width of 50% of the stiffener spacing (Figure 6.37), a doubler edge distance of 254 mm results in the lowest hot spot stress. Also at this edge distance, hot spot stress level drops with increase in corrosion aspect ratio.

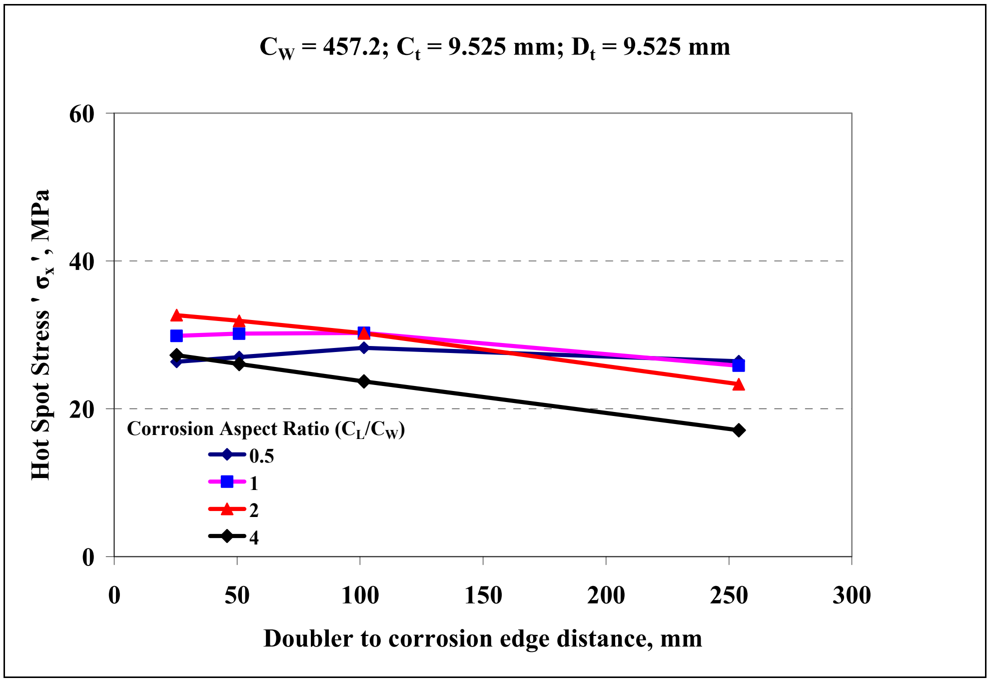


Figure 6.37: Effect of Doubler Size for D_t = 9.525 mm and C_W = 457.2 mm

6.2.8.3 Effect of Doubler Edge Distance and Corrosion Aspect Ratio on Hot Spot Stress for CW = 762 mm

The combination of a larger doubler edge distance and a larger corrosion aspect ratio gives the lowest hot spot stress (Figures 6.38 and 6.39). As the doubler edge distance increases the hot spot stress level decreases.

The hot spot stress decreases as the corrosion aspect ratio increases. The size of the doubler depends on the size of the corrosion feature; larger corrosion areas employ larger doubler plates. At corrosion width of 84% of the stiffener spacing, as the corrosion aspect ratio and doubler edge distance increases the size of the doubler increases thereby stiffening up the corroded panel and providing more resistance against lateral loading.

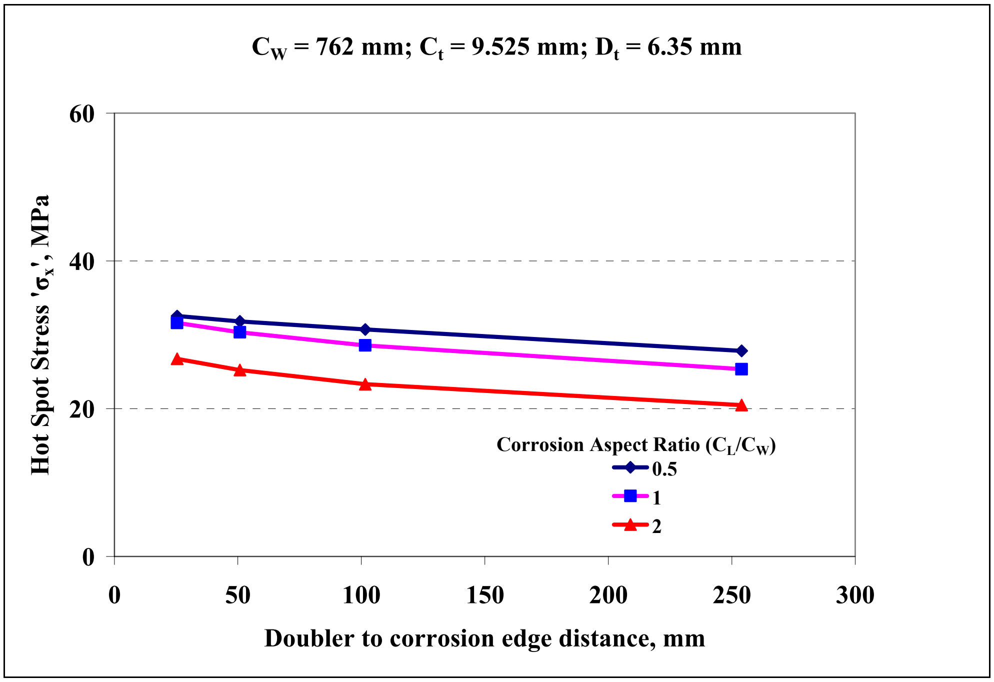


Figure 6.38: Effect of Doubler Size for D_t = 6.35 mm and C_W = 762 mm

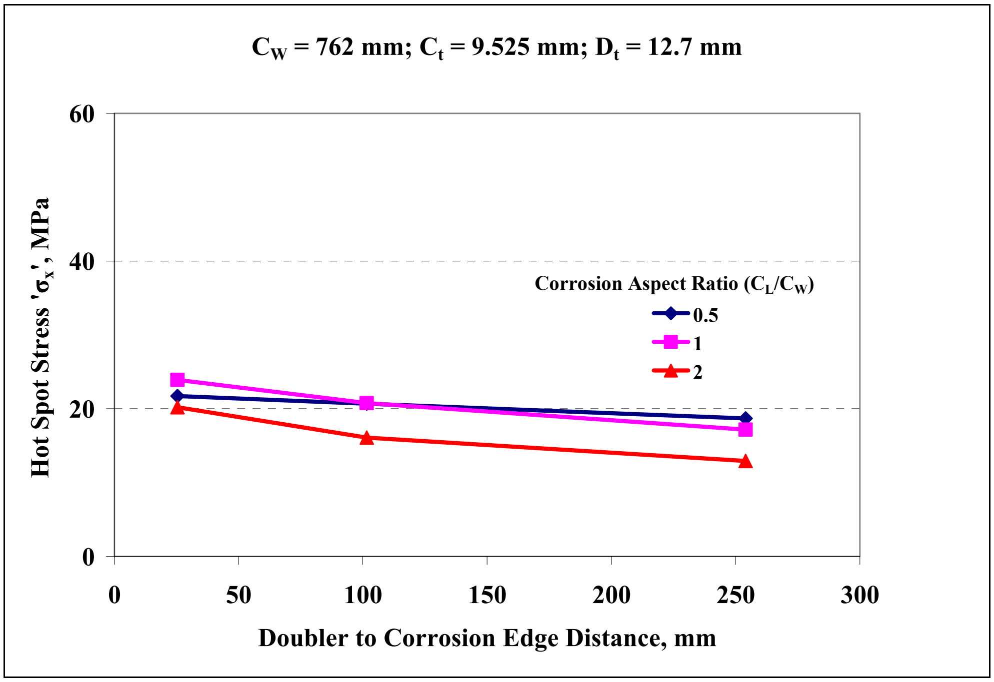


Figure 6.39: Effect of Doubler Size for D_t = 12.7 mm and C_W = 762 mm

6.2.8.4 Effect of Doubler Thickness Factor

Figures 6.40 and 6.41 illustrate the effect of doubler thickness factor on hot spot stress. It can be seen that a thicker doubler will reduce the hot spot stress and thus enhance the fatigue strength of corroded stiffened subjected to lateral loading.

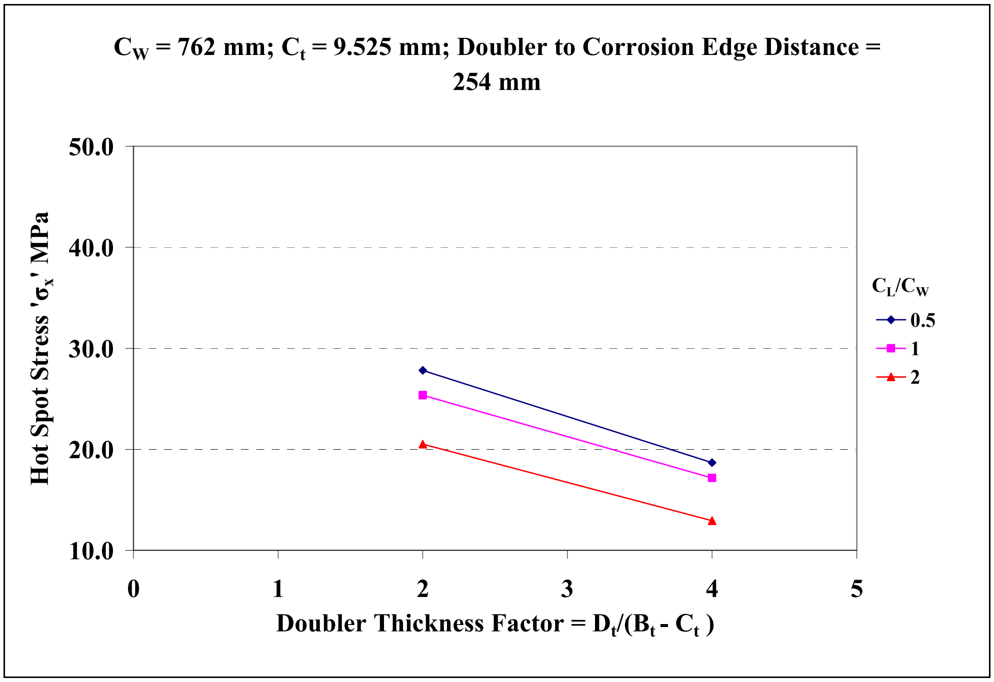


Figure 6.40: Effect of Doubler Thickness Factor for C_W = 762 mm

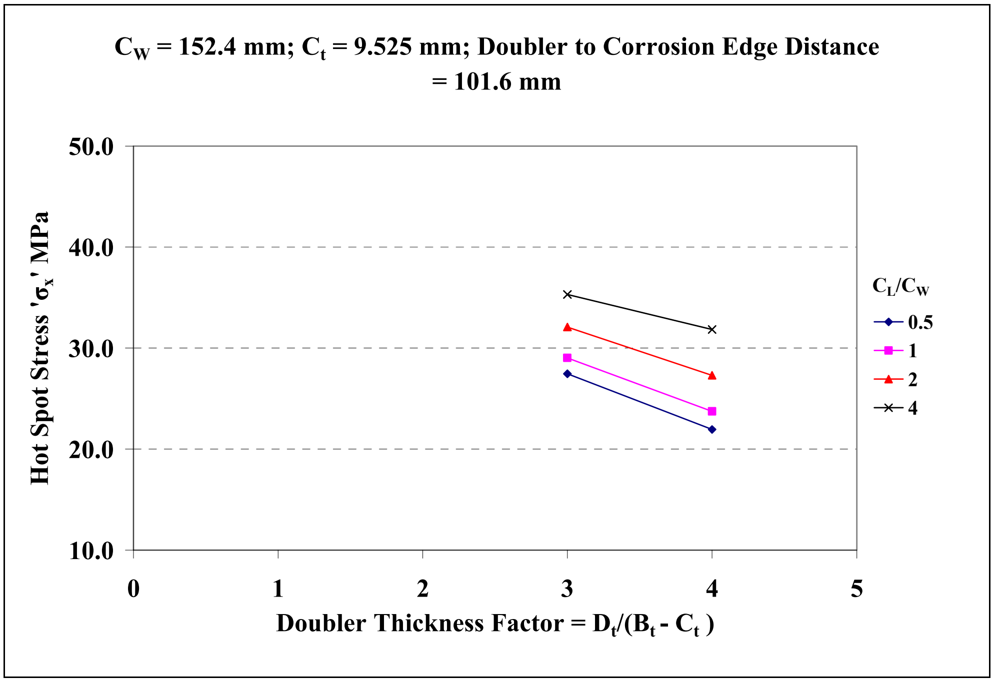


Figure 6.41: Effect of Doubler Thickness Factor for C_W = 152.4 mm

6.2.9 Combined Loading Effect (Tension + Lateral)

For a linear analysis, theoretically by superposition of hot spot stresses from tensile and lateral load cases, stresses generated from combined loading can be predicted. The application of combined loading would represent the worst case scenario. Tables 6.6 through 6.10 summarize the hot spot stress results for combined loading scenario (tension +lateral) for load cases from Table 6.4 and 6.5.

Table 6.6: Hot Spot Stress (MPa) @ D_t = 12.7 mm; C_W = 152.4 mm

Corrosion Aspect Ratio	Doubler to Corrosion Edge Distance, mm			
	25.4	**50.8**	**101.6**	**254**
0.5	99	101	107	122
1	108	109	114	126
2	124	124	126	130
4	146	144	142	134

Table 6.7: Hot Spot Stress (MPa) @ D_t = 9.525 mm; C_W = 457.2 mm

Corrosion Aspect Ratio	Doubler to Corrosion Edge Distance, mm			
	25.4	**50.8**	**101.6**	**254**
0.5	110	113	119	126
1	125	127	129	129
2	138	137	135	129
4	136	134	131	125

Table 6.8: Hot Spot Stress (MPa) @ D_t = 6.35 mm; C_W = 762 mm

Corrosion Aspect Ratio	Doubler to Corrosion Edge Distance, mm			
	25.4	**50.8**	**101.6**	**254**
0.5	122	123	124	127
1	129	128	127	127
2	127	126	124	124
4	125	123	121	86

Table 6.9: Hot Spot Stress (MPa) @ D_t = 12.7 mm; C_W = 762 mm

Corrosion Aspect Ratio	**Doubler to Corrosion Edge Distance, mm**		
	25.4	**101.6**	**254**
0.5	110	115	119
1	125	123	122
2	127	122	120

Table 6.10: Hot Spot Stress (MPa) @ D_t = 9.525 mm; C_W = 152.4 mm

Corrosion Aspect Ratio	**Doubler to Corrosion Edge Distance, mm**		
	25.4	**50.8**	**101.6**
0.5	105	108	115
1	114	116	121
2	128	129	132
4	145	144	143

6.2.9.1 Effect of Doubler Edge Distance on Combined Loading

Figures 6.42 and 6.43 illustrate the effect of doubler edge distance on combined hot spot stress for C_w =152.4 mm and C_w = 762 mm, respectively, where C_w is the width of the corrosion feature. As noted earlier the results for the very large aspect ratio corrosion features (aspect ratio =4) are affected by the extents of the FE model and thus have a trend that does not agree well with those produced for smaller corrosion features. The results shown in Figure 6.42 (C_w =152.4 mm) indicates that in general the weld toe hot spot stress increases with doubler edge distances for corrosion feature aspect ration of 2 or less. For larger values of corrosion aspect ratio, the hot spot stress decreases as the doubler edge distance increases. Figure 6.43 (C_w = 762 mm) indicates that for corrosion aspect ratio of 0.5, the hot spot stress increases as the overlap between the base plate and doubler plate increases (i.e. with increase in corrosion edge distance). The hot spot stresses for higher corrosion aspect ratios decrease with the corrosion edge distance. From the inspection of these two figures, the doubler to corrosion edge distance should be kept less than 100 mm to minimize the effect of edge distance on fatigue life.

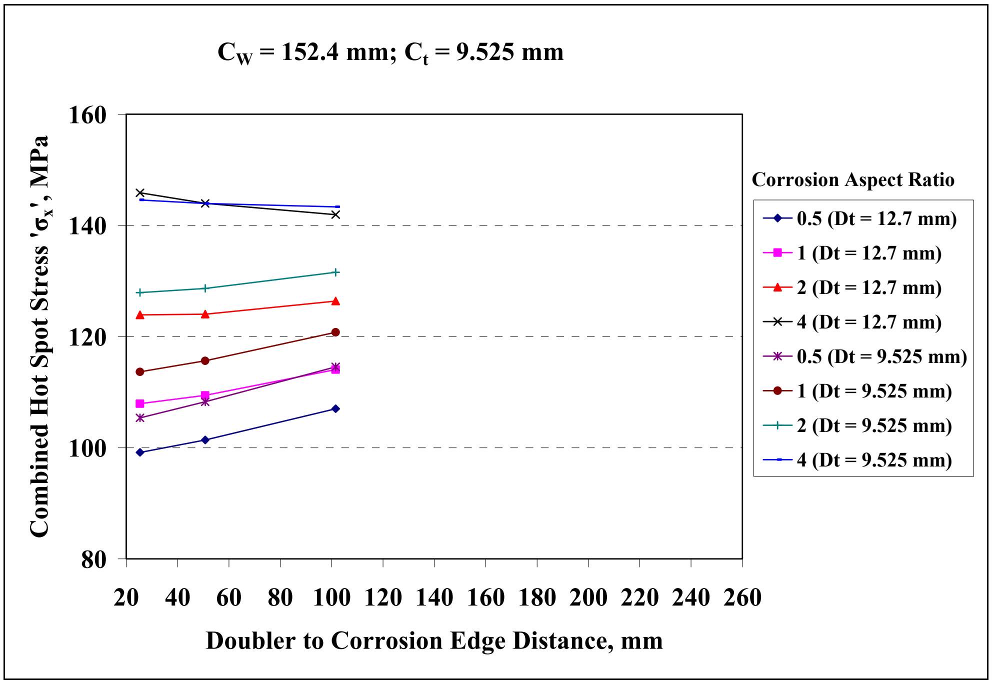


Figure 6.42: Effect of Doubler Edge Distance @ C_W = 152.4 mm

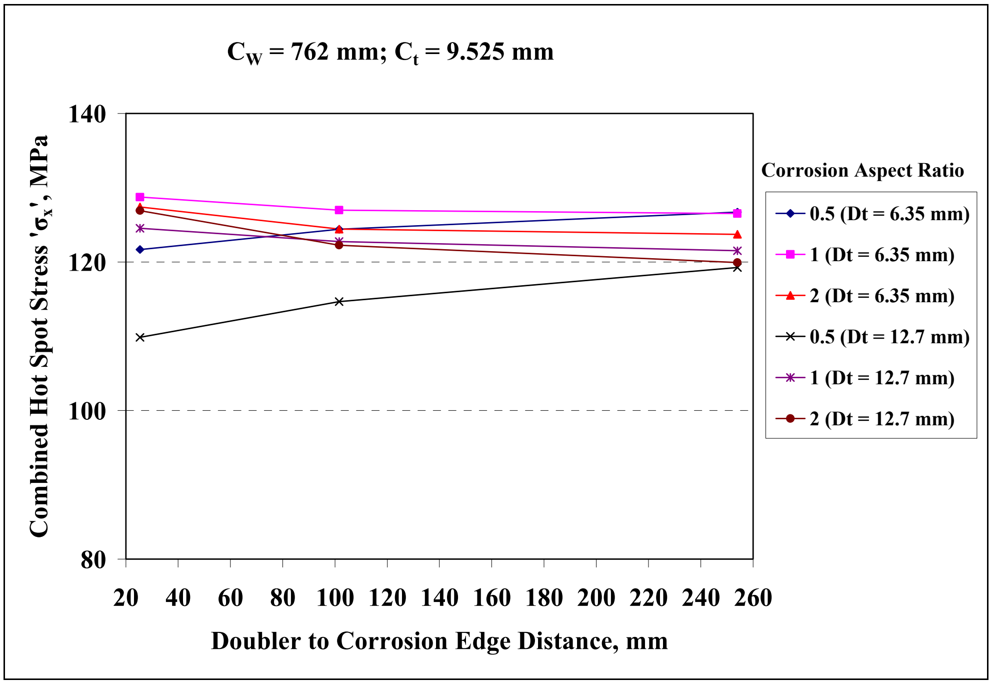


Figure 6.43: Effect of Doubler Edge Distance @ C_W = 762 mm

6.2.9.2 Effect of Doubler Thickness Factor on Combined Loading

Figures 6.44 and 6.45 illustrate the effect of doubler thickness factor (as defined in Section 5.2.5.4) on combined hot spot stress. A thicker doubler will reduce weld hot spot stresses and thus increase the fatigue strength of corroded stiffened panel. It is suggested, therefore, that higher thickness doublers be used to repair the damage done by corrosion, however, the reduction in hot spot stress level will need to be weighed against the cost of the thicker doubler since the reduction in hot spot stresses is not large.

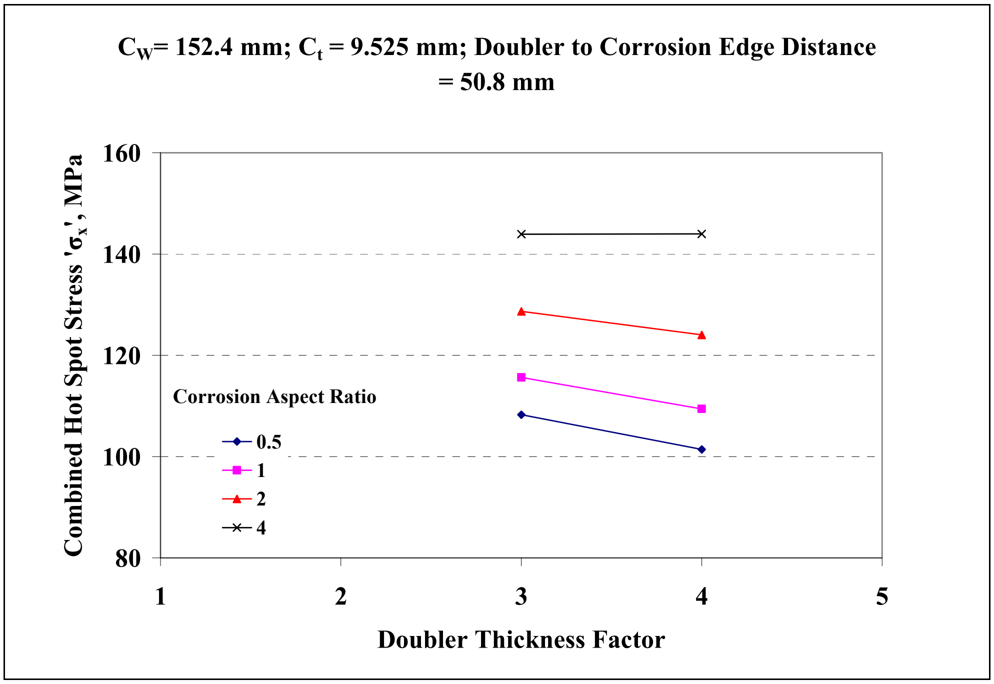


Figure 6.44: Effect of Doubler Thickness Factor @ C_W = 152.4 mm

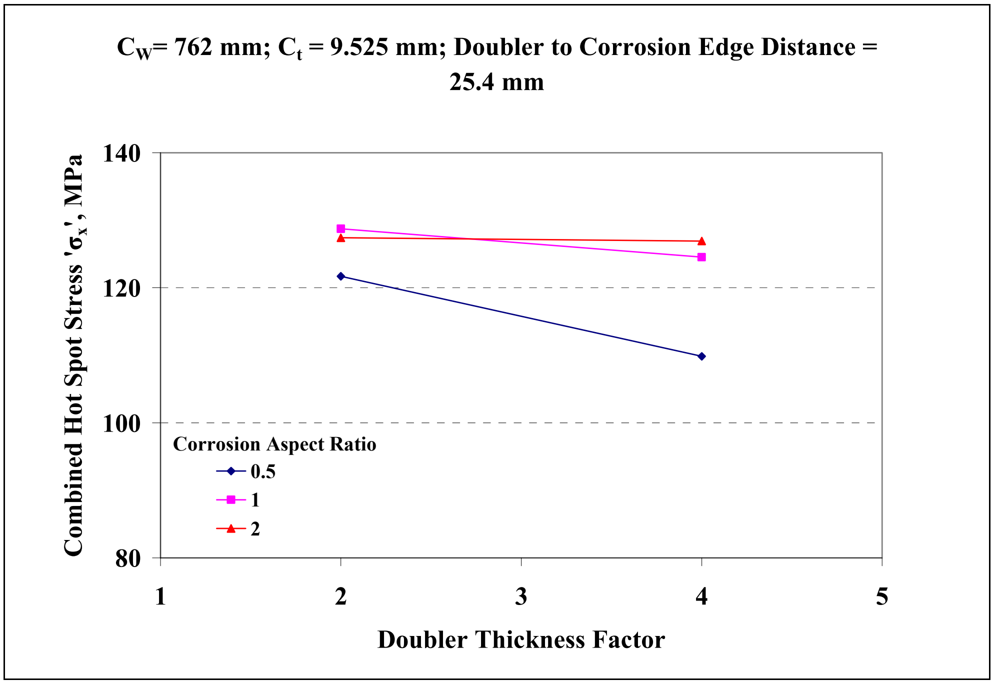


Figure 6.45: Effect of Doubler Thickness Factor @ C_W = 762 mm

6.2.10 Doubler Recommendations

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Doubler, D_t, thickness should always be greater than $0.5*B_t$
- Doubler thicknesses, should be as large as reasonable
- Doubler to corrosion edge distance should be kept as small as possible and certainly be less than 100 mm

6.3 Effect Of Location Of Corrosion Center W.R.T. Stiffener And Slot Welds

To study the effect of location of corrosion with respect to stiffener and slot welds; two scenarios were considered (Figures 6.46 and 6.47). In addition to constant parameters listed in Table 6.3, a constant doubler to corrosion edge distance of 50.8 mm has been used. Table 6.11 and 6.12 summarizes the doubler and corrosion parameters and hot spot result summary for tensile and lateral loading scenarios. To study effect of slot welding doubler plates, a single row of slot welds along the length of the doubler has been considered. The corroded feature and slot welds are assumed to be asymmetric about global XY plane.

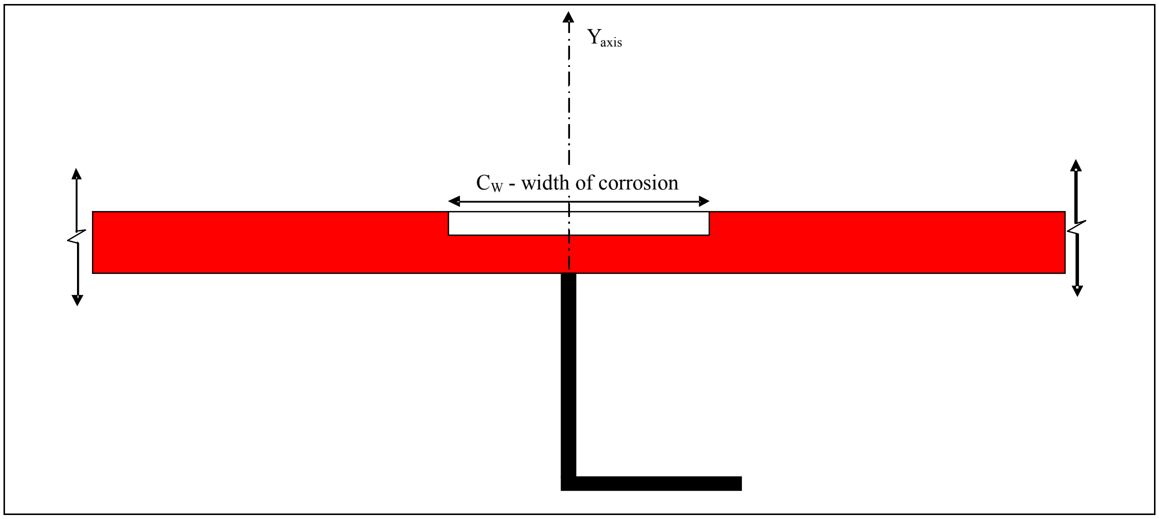


Figure 6.46: Center of corrosion aligned with stiffener

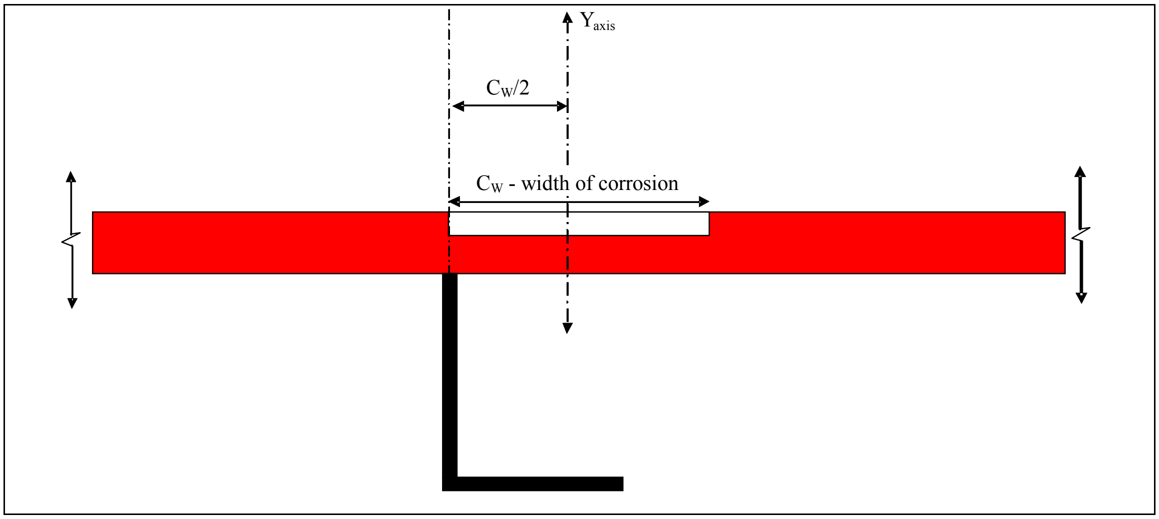


Figure 6.47: Center of corrosion at w/2 from stiffener

The finite element models developed for this investigation are similar to those described in Section 6.2. The model boundary conditions are also the same.

6.3.1 Material Model

The material models used in this investigation are the same as those described in Section 6.2.3.

6.3.2 Loading

The applied loading is the same as that described in Section 6.2.6.

6.3.3 Hot Spot Stress Analysis

In these analyses, the hot spot stress is calculated at the weld toe location, P1, as illustrated in Figure 6.49 below. The stress at weld toe is linearly extrapolated from those at distance t/2 and 3t/2 from weld toe, where, 't' is the thickness of stiffened panel.

6.3.4 Result Summary -Tensile Loading

Table 6.11 summarizes the results for corroded stiffened panel with doubler subjected to tensile loading. Stress plots for few selected cases are shown in Appendix C (Figures C.19 through C.21).

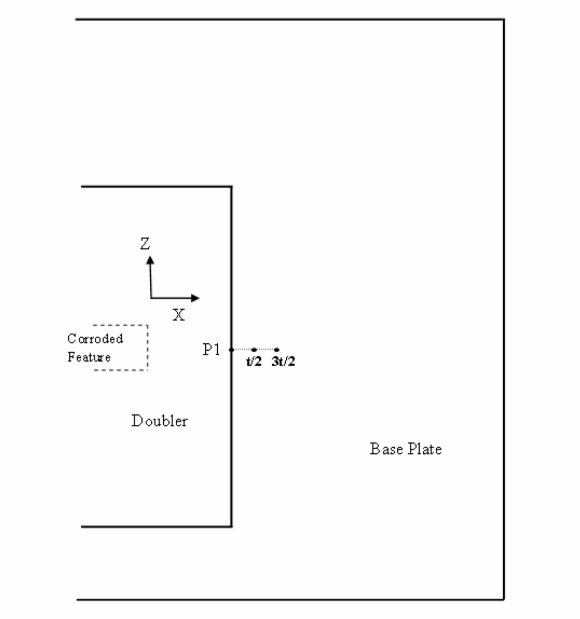


Figure 6.48: Hot Spot Stress Location

6.3.4.1 Effect of Slot Welds

Figures 6.49 through 6.51 illustrate the effect of slot welding a doubler on corroded stiffened panel, where the location of the corrosion feature is asymmetric with respect to global XY plane. For a constant doubler edge distance, as the corrosion aspect ratio increases, slot welding the doubler plate has a greater effect as it lowers the hot spot stress levels.

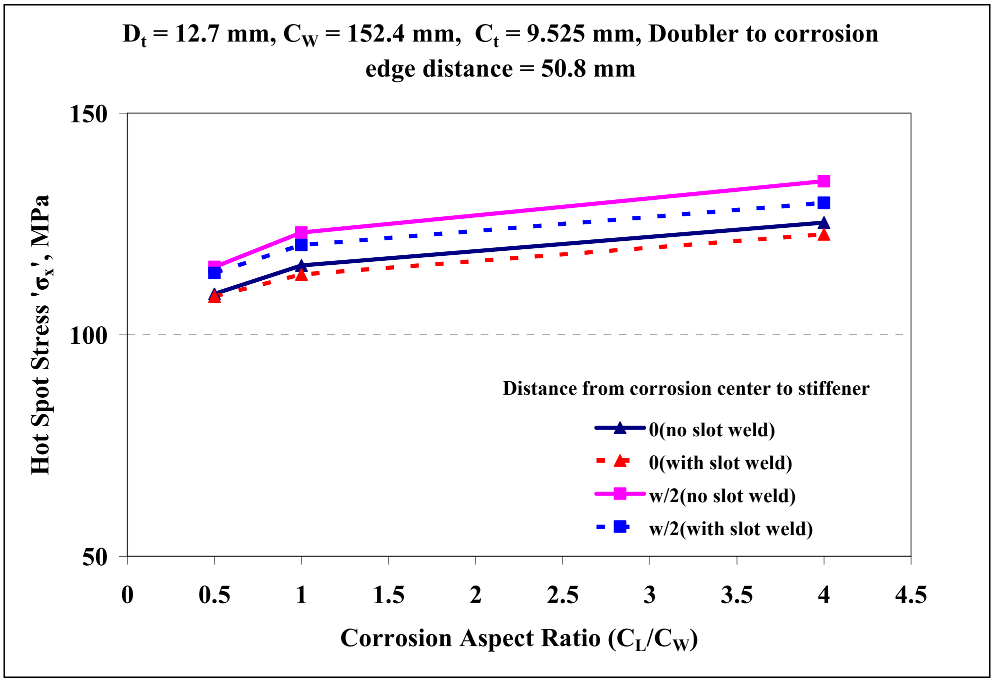


Figure 6.49: Effect of Slot Welds @ D_t = 12.7 mm and C_W = 152.4 mm

Table 6.11: Tensile Loading Summary

Case No.	Doubler Thickness, mm D_t	Corroded Feature, mm			Distance from Corrosion center to stiffener	Slot Weld	Size of Slot Weld, mm			Hot Spot Stress, 'σ_X'
		Thick C_t	Width C_W	Length C_L	mm		Length	Width	Pitch	MPa
1	12.7	9.525	152	76	0	NO	-	-	-	109.2
2	12.7	9.525	152	152	0	NO	-	-	-	115.6
3	12.7	9.525	152	610	0	NO	-	-	-	125.3
4	9.525	9.525	457	229	0	NO	-	-	-	116.3
5	9.525	9.525	457	457	0	NO	-	-	-	124.2
6	9.525	9.525	457	1829	0	NO	-	-	-	127.7
7	6.35	9.525	762	381	0	NO	-	-	-	111.1
8	6.35	9.525	762	762	0	NO	-	-	-	115.6
9	6.35	9.525	762	3048	0	NO	-	-	-	104.6
10	12.7	9.525	152	76	76.2	NO	-	-	-	115.3
11	12.7	9.525	152	152	76.2	NO	-	-	-	123.1
12	12.7	9.525	152	610	76.2	NO	-	-	-	134.7
13	9.525	9.525	457	229	228.6	NO	-	-	-	96.2
14	9.525	9.525	457	457	228.6	NO	-	-	-	105.0
15	9.525	9.525	457	1829	228.6	NO	-	-	-	113.3
16	6.35	9.525	762	381	381	NO	-	-	-	92.1
17	6.35	9.525	762	762	381	NO	-	-	-	98.4
18	6.35	9.525	762	3048	381	NO	-	-	-	103.5
19	12.7	9.525	152	76	0	YES	76.2	25.4	152.4	108.7
20	12.7	9.525	152	152	0	YES	76.2	25.4	152.4	113.6
21	12.7	9.525	152	610	0	YES	76.2	25.4	152.4	122.7
22	9.525	9.525	457	229	0	YES	76.2	19.05	152.4	113.7
23	9.525	9.525	457	457	0	YES	76.2	19.05	152.4	116.6
24	9.525	9.525	457	1829	0	YES	76.2	19.05	152.4	121.3
25	6.35	9.525	762	381	0	YES	76.2	12.7	152.4	108.9
26	6.35	9.525	762	762	0	YES	76.2	12.7	152.4	112.2
27	6.35	9.525	762	3048	0	YES	76.2	12.7	152.4	103.9
28	12.7	9.525	152	76	76.2	YES	76.2	25.4	152.4	113.9
29	12.7	9.525	152	152	76.2	YES	76.2	25.4	152.4	120.3
30	12.7	9.525	152	610	76.2	YES	76.2	25.4	152.4	129.8
31	9.525	9.525	457	229	228.6	YES	76.2	19.05	152.4	97.6
32	9.525	9.525	457	457	228.6	YES	76.2	19.05	152.4	105.5
33	9.525	9.525	457	1829	228.6	YES	76.2	19.05	152.4	110.5
34	6.35	9.525	762	381	381	YES	76.2	12.7	152.4	92.9
35	6.35	9.525	762	762	381	YES	76.2	12.7	152.4	98.0
36	6.35	9.525	762	3048	381	YES	76.2	12.7	152.4	100.5

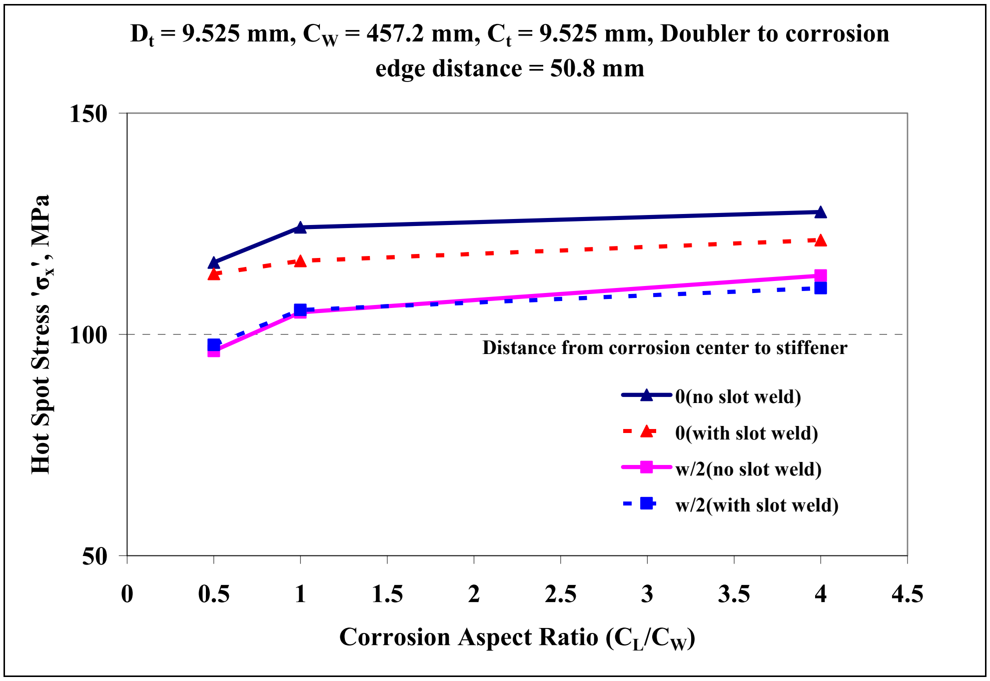


Figure 6.50: Effect of Slot Welds @ D_t = 9.525 mm and C_W = 457.2 mm

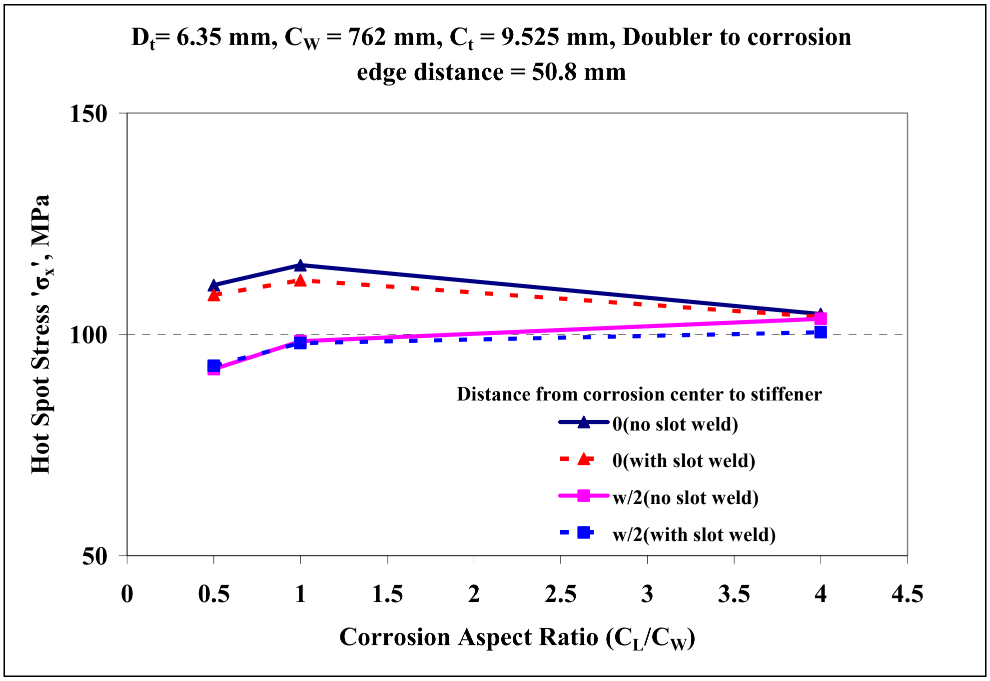


Figure 6.51: Effect of Slot Welds @ D_t = 6.35 mm and C_W = 762 mm

It is also clear from the figures above that the slot welds applied along the stiffener are more effective in reducing hot spot stress levels compared to slot welds applied at a distance of $C_w/2$ from the stiffener, where C_w is the width of the corrosion feature.

6.3.4.2 Conclusion

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Slot welding the doubler, strengthens the corroded stiffened panel. The location of corroded feature with respect to stiffener affects the strength of the stiffened panel.
- The larger the corrosion aspect ratio the more significant the effect of slot welds becomes.
- Slot welds are most effective if they are applied along the tops of the stiffener.

6.3.5 Result Summary - Lateral Loading

Table 6.12 summarizes the results for corroded stiffened panel with doubler subjected to lateral loading.

Table 6.12: Lateral Loading Summary

Case No.	Doubler Thickness, mm D_t	Corroded Feature, mm			Distance from Corrosion center to stiffener	Slot Weld	Size of Slot Weld, mm			Hot Spot Stress, 'σ_X'
		Thick C_t	Width C_W	Length C_L	mm		Length	Width	Pitch	MPa
1	12.7	9.525	152	76	0	NO	-	-	-	39.8
2	12.7	9.525	152	152	0	NO	-	-	-	43.6
3	12.7	9.525	152	610	0	NO	-	-	-	50.1
4	9.525	9.525	457	229	0	NO	-	-	-	41.2
5	9.525	9.525	457	457	0	NO	-	-	-	45.2
6	9.525	9.525	457	1829	0	NO	-	-	-	43.4
7	6.35	9.525	762	381	0	NO	-	-	-	39.6
8	6.35	9.525	762	762	0	NO	-	-	-	41.6
9	6.35	9.525	762	3048	0	NO	-	-	-	24.1
10	12.7	9.525	152	76	76.2	NO	-	-	-	41.7
11	12.7	9.525	152	152	76.2	NO	-	-	-	46.1
12	12.7	9.525	152	610	76.2	NO	-	-	-	53.1
13	9.525	9.525	457	229	228.6	NO	-	-	-	32.6
14	9.525	9.525	457	457	228.6	NO	-	-	-	35.7
15	9.525	9.525	457	1829	228.6	NO	-	-	-	31.7
16	6.35	9.525	762	381	381	NO	-	-	-	32.1
17	6.35	9.525	762	762	381	NO	-	-	-	30.8
18	6.35	9.525	762	3048	381	NO	-	-	-	16.4
19	12.7	9.525	152	76	0	YES	76.2	25.4	152.4	39.5
20	12.7	9.525	152	152	0	YES	76.2	25.4	152.4	43.1
21	12.7	9.525	152	610	0	YES	76.2	25.4	152.4	50.1
22	9.525	9.525	457	229	0	YES	76.2	19.05	152.4	40.4
23	9.525	9.525	457	457	0	YES	76.2	19.05	152.4	42.8
24	9.525	9.525	457	1829	0	YES	76.2	19.05	152.4	42.6
25	6.35	9.525	762	381	0	YES	76.2	12.7	152.4	38.4
26	6.35	9.525	762	762	0	YES	76.2	12.7	152.4	39.9
27	6.35	9.525	762	3048	0	YES	76.2	12.7	152.4	23.8
28	12.7	9.525	152	76	76.2	YES	76.2	25.4	152.4	41.4
29	12.7	9.525	152	152	76.2	YES	76.2	25.4	152.4	45.4
30	12.7	9.525	152	610	76.2	YES	76.2	25.4	152.4	52.0
31	9.525	9.525	457	229	228.6	YES	76.2	19.05	152.4	33.0
32	9.525	9.525	457	457	228.6	YES	76.2	19.05	152.4	35.9
33	9.525	9.525	457	1829	228.6	YES	76.2	19.05	152.4	31.9
34	6.35	9.525	762	381	381	YES	76.2	12.7	152.4	32.6
35	6.35	9.525	762	762	381	YES	76.2	12.7	152.4	31.1
36	6.35	9.525	762	3048	381	YES	76.2	12.7	152.4	15.1

6.3.5.1 Effect of Slot Welds

Figures 6.52 through 6.54 illustrate the effect of slot welding a doubler on corroded stiffened panel, where the location of the corrosion feature is asymmetric with respect to global XY plane.

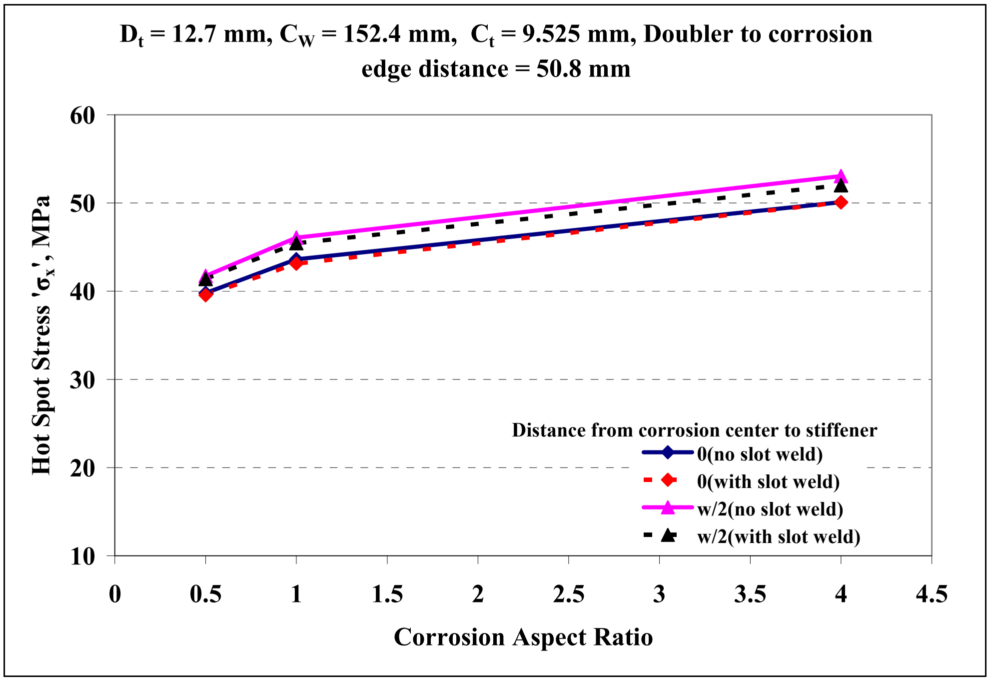


Figure 6.52: Effect of Slot Welds @ D_t = 12.7 mm and C_W = 152.4 mm

Figures 6.52 and 6.53 illustrate that for doubler plates with thickness more than 75% of the base plate, slot welding the doubler plate along the stiffener (Figure 6.46) enhances the strength of corroded panel. For scenarios where the edge of corroded feature is aligned with the stiffener (Figure 6.47), slot welding the doubler plate is not very effective. However, when the double plate thickness is around half the thickness of the base plate, slot welding doubler plates does not seem to provide any significant stress reduction (Figure 6.54). Increasing the number of rows of slot weld along the width of doubler would lower weld toe stress, however, this would develop an increased number of fatigue crack initiation sites.

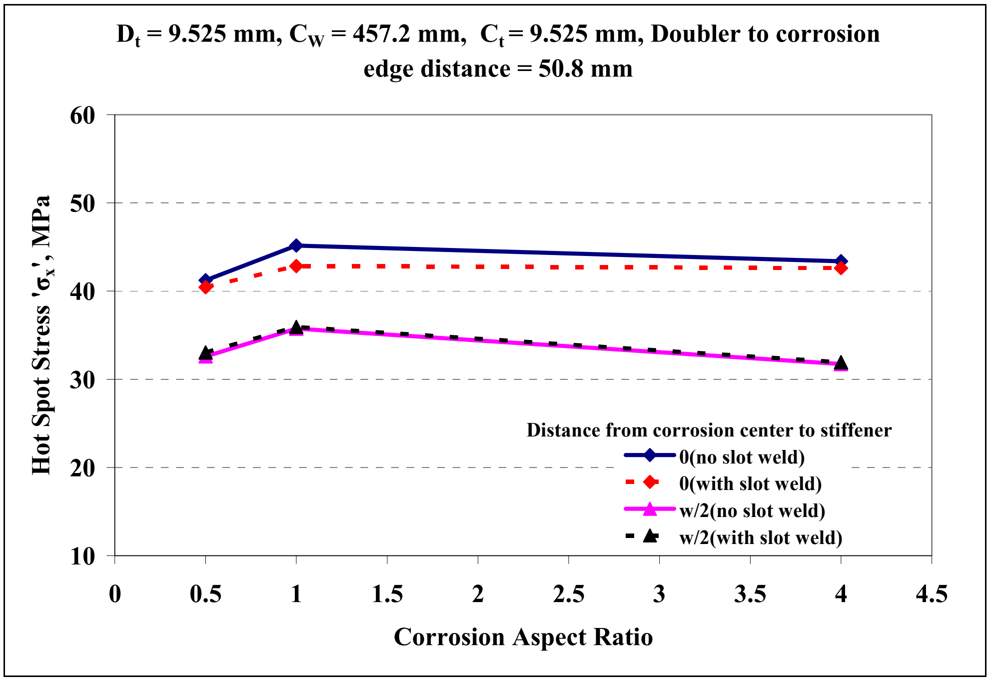


Figure 6.53: Effect of Slot Welds @ $D_t = 9.525$ mm and $C_W = 457.2$ mm

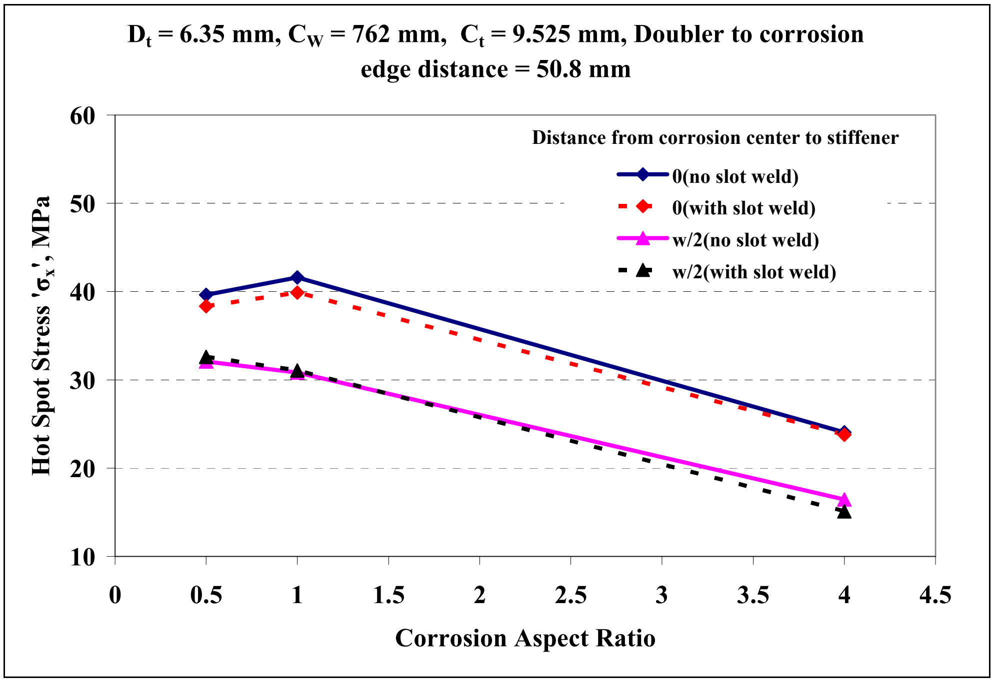


Figure 6.54: Effect of Slot Welds @ $D_t = 6.35$ mm and $C_W = 762$ mm

6.3.5.2 Conclusion

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Slot welding the doubler, strengthens the corroded stiffened panel. The location of corroded feature with respect to stiffener affects the strength of the stiffened panel.
- Increasing the number of rows of slot weld along doubler width would strengthen the corroded stiffened panel; however this increase in the number of slot welds would also introduce a great number of potential crack initiation sites.
- For doubler size and thickness, recommendations from Section 6.2 should be followed.

6.3.6 Combined Loading Effect (Tension + Lateral)

For a linear analysis the lateral and tensile applied loading can theoretically be combined by superposition. The application of combined loading would represent the worst-case scenario. Tables 6.13 through 6.15 summarize the hot spot stress results for combined loading for load cases from Table 6.11 and 6.12. The following notations are used in these tables:

- 0, and $C_W/2$: Distance between Corrosion Center and Stiffener
- NS: No slot weld
- WS: With slot weld

Table 6.13: Hot Spot Stress (MPa) @ D_t = 12.7 mm; C_W = 152.4 mm

Corrosion Aspect Ratio	Combined Hot Spot Stress 'σ_X', MPa			
	0- NS	0-WS	C_W/2-NS	C_W/2-WS
0.5	149	148	157	155
1	159	157	169	166
4	175	173	188	182

Table 6.14: Hot Spot Stress (MPa) @ D_t = 9.525 mm; C_W = 457.2 mm

Corrosion Aspect Ratio	Combined Hot Spot Stress 'σ_X', MPa			
	0- NS	0-WS	C_W/2-NS	C_W/2-WS
0.5	158	154	129	131
1	169	159	141	141
4	171	164	145	142

Table 6.15: Hot Spot Stress (MPa) @ D_t = 6.35 mm; C_W = 762 mm

Corrosion Aspect Ratio	Combined Hot Spot Stress 'σ_X', MPa			
	0- NS	0-WS	C_W/2-NS	C_W/2-WS
0.5	151	147	124	125
1	157	152	129	129
4	129	128	120	116

Figures 6.55 through 6.57 illustrate the effect of combined loading on hot spot stress for change in corrosion location and slot welding the doubler. The effect of slot welding the doubler is more pronounced as the corrosion aspect ratio increases.

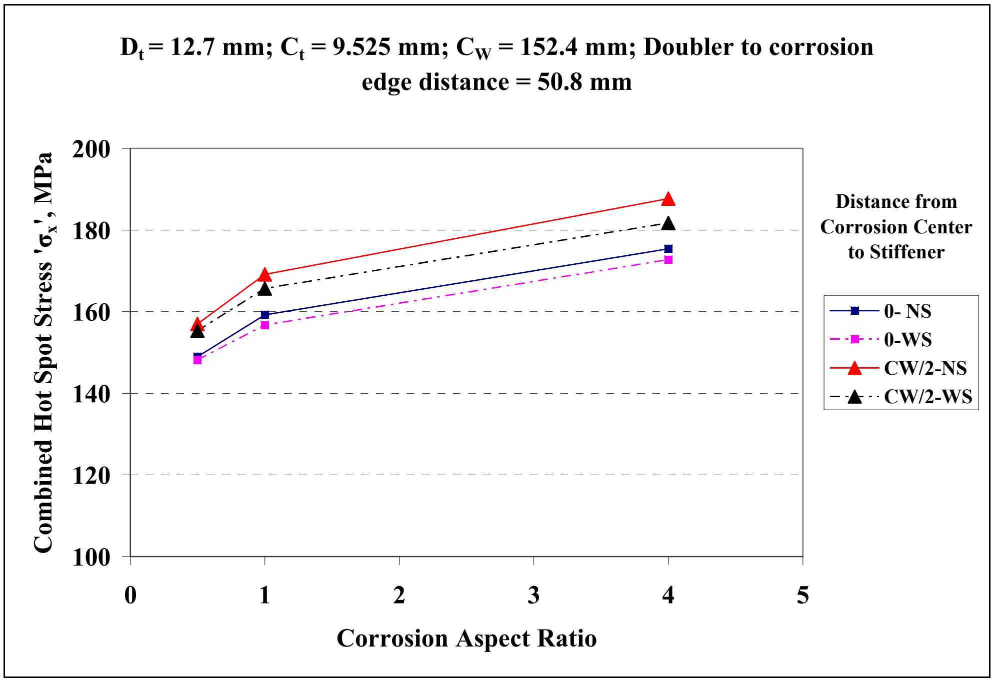


Figure 6.55: Effect of Combined Loading @ D_t = 12.7 mm and C_W = 152.4 mm

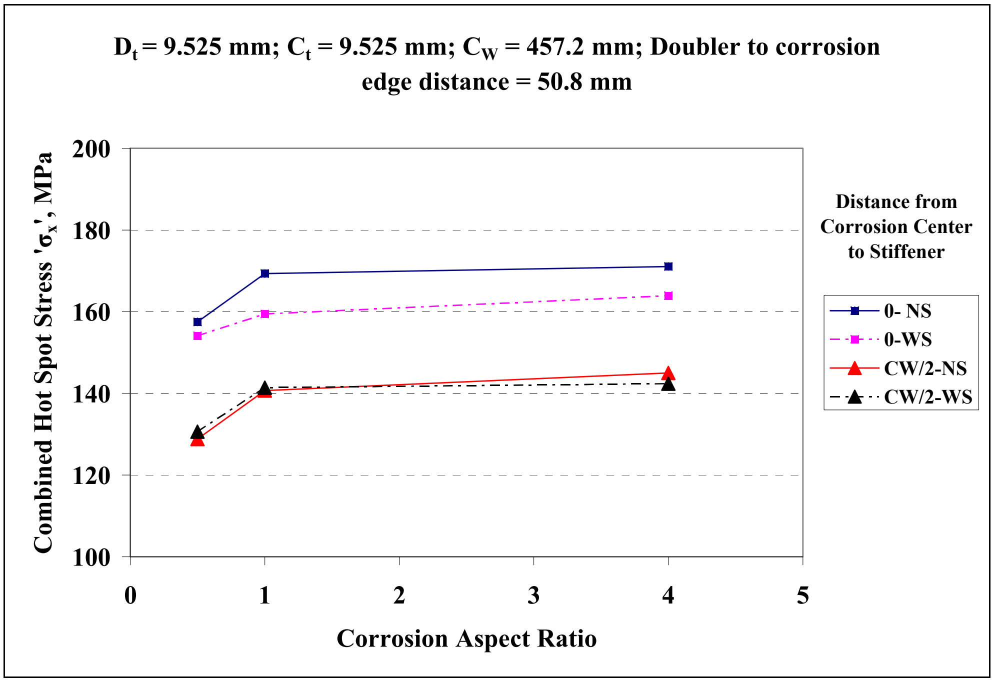


Figure 6.56: Effect of Combined Loading @ D_t = 9.525 mm and C_W = 457.2 mm

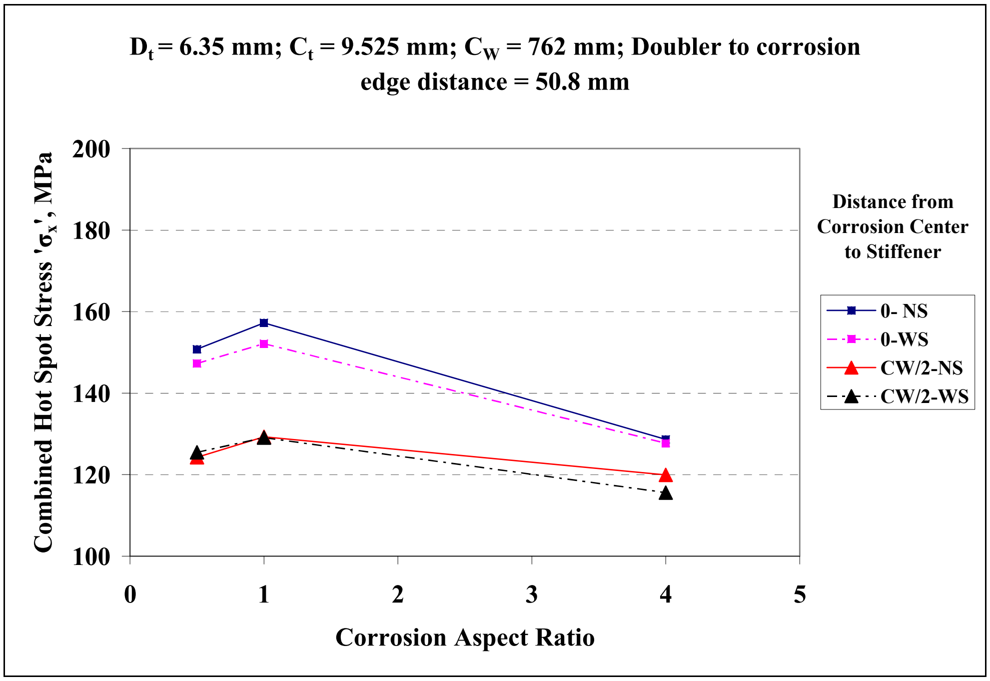


Figure 6.57: Effect of Combined Loading @ D_t = 6.35 mm and C_W = 762 mm

6.3.7 Recommendations

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Slot welding on larger doubler plates is recommended for corroded stiffened panel.
- Increasing the number of rows of slot weld along doubler width would strengthen the corroded stiffened panel; however, this increases the number potential fatigue crack initiation sites.
- For doubler size and thickness, recommendations from Section 6.2 should be followed.

6.4 Effect of Residual Stress

In the initial project plan, it was proposed to investigate residual stress effects on fatigue and fracture. In general, higher residual stresses will increase fatigue crack growth rates and the potential for fracture, but not plastic collapse. In completing the project, local stress due to the applied loading was used as a surrogate for fatigue and fracture driving force. The design criteria were developed to ensure that the doubler repair had the same or better performance (yield strength, buckling, fatigue, and fracture resistance) as the original structure. With this approach taken the effect of residual stress is reduced to a secondary effect in which high levels of non-uniformly distributed residual stress could result in distortion that would reduce buckling loads or promote secondary bending that would enhance fatigue crack initiation or growth. For this reason residual stresses were not considered.

7.0 CORROSION BEHAVIOR

7.1 Corrosion Considerations for Doubler Plates

An important factor to be considered in the stress analysis of doubler plate repairs is the estimated reduction of material and effects due to corrosion. There are multiple ways in which corrosion can damage structures, in particular with consideration of the more aggressive types of corrosion with localized effects (specifically of the weldment), general wasting or a combination of both.

This section first provides a literature review of related work. This is followed by a discussion of 1) Probabilistic, 2) Deterministic models and 3) Empirical approaches estimating the corrosion behavior of ship structures. Discussion of the mechanisms of corrosion with respect to doubler plates is discussed and a variation of an existing model is used. Correlation of the predicted behavior with a survey of shipyards on doubler plates is presented.

7.2 Literature Review

7.2.1 Ship Structure Committee Reports

Several ship structure committee reports have investigated the behavior of corrosion with respect to fatigue and repair welding issues.

Most recently, Dexter, Fitzpatrick and St. Peter (2003) in SSC-425 investigated fatigue behavior that consisted of tests performed to generate S-N (stress vs. number of cycle to failure) curves for ship structure configurations in areas subject to fatigue. Included in the evaluation were doubler plates used as a repair for cracking. The crack was first repaired and then a doubler was then applied over the repair. The repair geometries were classified for fatigue based on AASHTO S-N curves. The doubler plate repair was categorized as a Class E or E' repair; considered undesirable in terms of fatigue life. In testing, however the doubler plates exceeded the AASHTO predicted values. The doubler plates were 18mm thickness x 76-102 mm wide and 203-254 mm in length, applied using SMAW with 7018 electrodes.

Jaske (2000) in SSC-412 considered corrosion in investigating the effect of cathodic protection on the fatigue of steel plate in synthetic seawater. The study included corrosion fatigue testing of butt-welded and fillet-welded joints as well as unwelded base metal specimens. It modeled the fatigue cracking occurred as the two stage crack initiation followed by crack propagation. It was reported that fatigue cracking occurred at the toes of the weld and not at the midspan of the specimen. In particular it was found that undercut weld toes had very low fatigue strength. Additionally, it was found that butt welds had higher fatigue resistance than the fillet welds. This report also included a very extensive bibliographic list with summaries.

Kirkhope, et al. in SSC-400 (1997) discussed methods to improve the fatigue behavior of weldments and includes protection from corrosion. It recommends weld toe grinding and other treatments to decrease corrosion losses with referenced fatigue studies of weld treatment in seawater and with cathodic protection. In this case configuration is double fillet weld that has bending moment applied. Another method that is recommended for improve corrosion resistance for welds is to hammer peen joints. It references studies that demonstrate that hammer peened welds reduce losses in both free corrosion and cathodic protection conditions.

Parente, Daidola, Basar and Rodi (1997), in SSC-397, provide a discussion of general corrosion protection for shipbuilding and maintenance. This includes a discussion of welding considerations to include avoidance of intermittent welds and lap joints due to concern for crevice corrosion. Consideration of joining techniques and the importance of proper welding specification is emphasized. Although corrosion rates are not quantified, the report makes general recommendations for corrosion behavior including welded joints.

Reynolds and Todd (1992) in SSC-366, conducted testing on HSLA welded steel for evaluation of corrosion fatigue in the Parent Metal (PM), Heat Affected Zone (HAZ) and Weld Metal (WM) regions and determined threshold stress levels for corrosion fatigue behavior.

Daidola and Parente (1996) SSC-394, detail corrosion behavior (specifically, pitting) of plates for ship structures. It was observed that pitting corrosion may occur preferentially at weld seams and butts and it is stated that the welds typically corrode 3-5 mm more than the surrounding plate in these areas. Two models are used to estimate the loss of plate thickness due to pitting.

Stambaugh and Knecht (1988) in SSC-348 provided an overview of corrosion behavior and data from ship structures. The corrosion behavior is categorized into eight classifications of corrosion as 1.General (Uniform), 2. Galvanic, 3. Crevice, 4. Pitting / Grooving, 5. Intergranular, 6.Selective Leaching, 7. Velocity Corrosion, and 8. Stress Corrosion Cracking. It discussed locations and conditions in which particular corrosion behavior occurred including mention of localized corrosion in the area of welds. A general overview of the methods for determination of corrosion rates was discussed.

Burnside, et al. (1984) in SSC-326 investigated corrosion fatigue to include consideration of weldments. The report determined the fatigue loading and then characterized fatigue cracking based on the stress condition with consideration of several variables to determine a crack growth rate for fatigue. Welded joints were specifically considered using a local strain approach. Analytical and experiment results were determined in air and in seawater. Corrosion fatigue of welded joints to include specifically addressing the sensitivity of weld toe geometry and local stress factors is detailed. A probabilistic model was used to characterize corrosion fatigue behavior.

Krumpton and Jordan, (1983) in SSC-323 considered geometry of fillet welds for ship structures, analyzes the stress state and makes recommendations. The focus was on ABS rules for welding although Navy welding requirements were also discussed. Included in the analysis is consideration of uniform corrosion of a weld to include a corrosion allowance. Intermittent welds were discussed separately to include a corrosion allowance for uniform corrosion.

7.3 Additional Investigations: Probabilistic and Deterministic Approaches

The most recent investigation on predicting corrosion and fatigue behavior for ship structures are summarized. These are primarily probabilistic approaches that are appropriate for characterizing large sets of data that have may have multiple variables. These studies have as a basis, a large field database of vessels in which the corrosion loss data may be subdivided into categories of particular locations and service conditions. As expected, this data has significant variability, but is useful in risk assessment conditions. By contrast, a deterministic approach may be used for a specific mechanism (for example, pitting). This type of approach is appropriate to quantify behavior if the particular corrosion mechanism is identified.

Wang, Spenser and Elsayed (2003a) used a probabilistic approach for a large database of approximately 110,000 thickness measurements in varied locations from 140 oil tankers (single hull). The paper lists factors for corrosion in oil tankers to include Coating Type and Longevity, Coating Application and Surface Preparation, Corrosivity of the Product, Inspection and Maintenance Strategies, Cathodic Protection, Trade Route, and others. Wang contrasts the three approaches for the analysis of corrosion rates is given as 1. Probabilistic representations, 2. Corrosion rate models, 3. Corrosion wastage databases. Wang recommends the probabilistic approach due to the variability of the data. Presented are corrosion rates for different locations with the mean, maximum and standard deviation. The results were compared with prior results from the TSCF (Tanker Structure Cooperative Forum) in the higher range of the results.

In Wang, Spenser and Sun (2003b), the database from the tanker study was used for the assessment of corrosion rates for aging ships. The corrosion wastage is ranked by three levels: slight, moderate, and severe levels corresponding to 50, 75 and 95% cumulative probability on the database which is thickness measurements taken by ABS (110000 on 140 oil tankers). It recommends a reliability based approach to model the uncertainties probabilistically vs. traditional engineering approaches which used deterministic approaches for a time variant process. It was found that the corrosion wastage had very high variability but that it exhibited an increasing trend in rate with the passage of time, i.e. the corrosion rate increased for aged ships.

Several studies have been conducted by Paik, et al. (2004(a), 2004(b), 2003(a), 2003(b), 1998(a), 1998(b), 1997) on corrosion analysis in several areas of ship structures.

Paik, et al. (2003a) formulated a mathematical model for time variant corrosion wastage of ship structures. This was used with statistical data of for both single and double hulled tankers and for FSOs (Floating Storage and Offshore loading units) and FPSOs (Floating Production, Storage, and Offshore loading units). The corrosion model additionally grouped structural members by type and location. The types of corrosion wastage typical to ship structures were identified as (a) general corrosion, (b) localized corrosion and (c) fatigue cracking from localized corrosion. The localized corrosion patterns typical to ship structures were identified as 1) Pitting, which typically occurs on bottom plating and at details that trap water and in particular aft tanks were identified 2) Grooving, described as "in line" pitting and 3) Weld Metal Corrosion, postulated as by galvanic action and initially characterized by pitting. The corrosion is modeled successively into three phases: 1) No corrosion while coating is intact, 2) Transition to Corrosion, and 3) Corrosion Progression. In the case of the Corrosion Progression stage, the time-dependent corrosion could be modeled as convex (decelerating with time) or as concave upward (accelerating with time). The depth of corrosion (t_r) was expressed as $t_r = C_1(T\text{-}T_c\text{-}T_t)^{C_2} = C_1T_e^{C_2}$, in which T= Structure Age, T_c = Time of Coating Durability, T_t =Transition Time and T_e = Time of Exposure under corrosion environment. The annualized corrosion rate (r_r) was defined as $r_r = C_1\ C_2T_e^{C_2\text{-}1}$. The constant C_1 is indicative of the annual corrosion rate and C_2 characterizes determines the trend of the corrosion process. The progress of corrosion stage is characterized by the mechanism of corrosion; which would be convex downward, for example for immersion general corrosion (due to scale formation). A concave upward curve represents increased corrosion which may be more applicable to dynamic conditions. The coating life variable T_c was fixed as 5, 7.5 and 10 years until breakdown, the coefficient C_2 was set equal to 1 for linear corrosion and C_1 was found by fitting statistical data for particular groupings, ship structure type and coating lifetimes. Included as conclusions from the study, was that the annualized corrosion rates followed a Weibull distribution, and that the rates differed for the different location/category groups. The range of most probable corrosion rates was from approximately .026 mm/year to .24 mm/year, but that the most severe corrosion rates could be several times higher.

In Paik, Wang, Thayamballi and Lee (2003b), the effect corrosion included both uniform corrosion as well as non-uniform pitting behavior in the investigation of aging ships. A DOP (degree of pitting) parameter characterized loss due to pitting of a plate. A time dependent corrosion model was detailed in which the behavior of was again characterized in three stages: 1) durability of coating, 2) transition stage and 3) progress of corrosion phase. Statistical analysis using the Weibull distribution with the mean value and COV are established. Fatigue behavior is also characterized. Reliability analysis for each, a bulk carrier, ship type FPSO and double walled tanker is preformed under multiple damage scenarios to ultimate longitudinal strength failure. The five damage scenarios used in the assessment included: 1) undamaged, 2) corrosion 3) corrosion + local dent damage, 4) corrosion + fatigue cracking, 5) corrosion + fatigue cracking + local dent damage for time dependent risk assessment of ships.

Paik (2004b) and Paik, Kim and Lee (2004b) were investigations of corrosion behavior of ballast tanks. Corrosion behavior was again modeled as initiating after the coating breakdown takes place which is varied at 5, 7.5 and 10 years. The corrosion depth formula was used as $t_r = C_1(T-T_c)$. The annual corrosion rate was linear as $r_r = C_1$. The mean value of parameter C_1 and the COV (coefficient of variation) were found for a Weibull statistical analysis. Results were summarized with C_1 and COV determined using a database of over 1900 data sets for the ballast tanks of bulk carriers and oil tankers. The results were then summarized and corrosions margins offered with sample calculations for each a representative bulk carrier and tanker.

Moan, Ayala-Uraga and Wang (2004) used a reliability method in evaluating FPSO structures formulation that includes fatigue and corrosion. The effect of corrosion on fatigue failure used a time dependent corrosion wastage was defined as $W(t) = R_{corr} \cdot \alpha(t-T_o)$ in which α is 1 in this case since the corrosion considered was one sided (α =2 for corrosion on both sides), T_o as the time for the corrosion protection system breakdown and R_{corr} as the annual wastage rate. The combination of corrosion wastage and fracture cracking was treated using a fracture mechanics model. A reliability model using the probability of failure based on crack growth is utilized to include corrosion modeled using a Weibull distribution analysis. The analysis also included consideration of the reliability level based on inspection for fatigue cracks and thickness measurements.

Guedes Soares and Gorbtov (1999a) used a reliability analysis for fatigue cracking, corrosion and their interaction with respect to failure of longitudinal members. It modeled fatigue cracking at joints of the midship section as well as corrosion of each plate in the midship section. From the classic Paris-Erdogan crack propagation equation $da/dN = C\Delta K^m$, in which a= crack length, N=number of stress cycles, ΔK= stress intensification factor and C is constant, a model is developed using a statistical treatment for fatigue stress with consideration of corrosion. In the corrosion analysis, the difference between general corrosion resulting in loss of plate thickness as well the more complicated behavior of pitting for localized perforation is addressed. It notes that the corrosion behavior is dependent on the protection system and separates the behavior into the two stages of 1.) Time of Coating Effectiveness followed by, 2.) Coating Effectiveness is lost and general corrosion occurs which was represented linearly as wastage. A Weibull distribution was used for reliability analysis for this time variant study which also included the effect of repair operations.

Guedes Soares and Gorbtov (1999b) provided a non-linear model of corrosion behavior of plates. It was stated that the two main corrosion mechanisms for plates are by general wastage and by pitting. The pitting of plates was not considered due to its localized nature. The general wastage was considered as non-linear behavior that levels out to a value d_∞ = long term thickness loss due to corrosion wastage. The three stages of corrosion wastage were modeled by the general equation $d_\infty \dot{d}(t) + d(t) = d_\infty$. The particular solution for the depth of corrosion, d, as a function of time (t), is given as $d(t) = 0$ for $t > \tau_c$, i.e. there is no corrosion during the time that the coating is effective (τ_c). This is followed by the solution of the depth of corrosion of $d(t) = d_\infty(1- e^{-(t-\tau_c/\tau_t)})$ for $t \leq \tau_c$, after the coating is no longer effective during the transition time stage τ_t , followed by the time of corrosion stage, τ_c . The corrosion model was tested using data from Paik, et al. (1998b). The corrosion loss was then incorporated into a reliability analysis for failure of the plate in compression to include decreased strength due to the loss of material due to corrosion.

Garbatov, Rudan and Guedes Soares (2002), used the above non-linear approximation for wastage to study fatigue damage with corrosion for knuckle joint and a bracket with a high stress concentration effect. The non-linear corrosion loss was used with the DNV formulations (1998a) for damage due to fatigue with consideration of corrosion based on a percentage loss in a corrosion environment.

Melchers (1999a) described a non-linear empirical model for general wastage of steel under immersion conditions using $d_w = .084t^{.823}$, in which d_w = uniform corrosion depth and t is the time of immersion. He has proposed a phenomenological model to consider each regime of corrosion using a probabilistic form of $c(t,E) = fn(t,E) + \varepsilon(t,E)$, in which $c(t,E)$ = weight loss function, $fn(t,E)$ = mean value function, $\varepsilon(t,E)$ = mean value function, t=time and E=environmental condition vector. The factors that affect corrosion behavior are also discussed to include, but not limited to, temperature, oxygen content, marine growth and water velocity. Melchers had designated the stages of marine corrosion are given as an initial kinetic controlled anodic behavior, followed by diffusion controlled behavior and the last stage is anaerobic controlled behavior. In Melchers (1999(b)), the large uncertainty in modeling corrosion behavior is discussed and he advocates for more extensive fundamental investigation of marine corrosion specifically.

Southwell (1979) provided a linear and bilinear model for general wastage due to immersion in seawater loss (mm) as a bilinear model of $d= .090t$ for $0.00\leq t< 1.46$ and $d = .076+.038t$ for $1.46\leq t< 16$ for higher temperature water in which d= depth of corrosion and t = time in years. The steel used was 1020 plain carbon steel and various conditions were addressed in the study that was conducted over a sixteen year study. The primary reason for having two regions in this case was due to the change in corrosion behavior after a significant fouling was present. Pitting was also analyzed and found to initially have corrosion rates on the order of 5-7 times greater than general wastage for the first two years and later to decrease to approximately 2.5 to 2.7 mils/year (.06-.07 mm/year); similar to the steady state long term general wastage rate. The decrease in the long term rate for pitting was also attributed to fouling.

Marine Corrosion behavior for ship structures is often assumed as linear behavior with a nominal rate of .1 mm/year used for general wastage unless otherwise defined. A summary of equations used for corrosion estimation are listed in Table 7.1.

Table 7.1: Summary of Relationships for Corrosion Behavior

Uniform Linear Corrosion Rate (Wastage)	$d = Ct$	d = depth of corrosion (mm or inch) C = corrosion rate (mm/yr), or mils/year (mil=10^{-3}inch) t = time
Southwell(1979) *Bilinear Model of steel immersed in seawater.*	$d = .090t$ $\quad 0.00 \leq t < 1.46$ $d = .076+.038t$ $\quad 1.46 \leq t < 16.$	d = depth of corrosion (mm) t = time (year)
Kondo (1989) *Pitting Corrosion Growth in a Fatigue Environment*	$c = C_p(N/f)^{1/3}$ $2c_{cr} = (2Q/\pi\alpha)[(\Delta K)_p/2.24\sigma_a]^2$	c = pit radius a = depth of pit α = a/c aspect ratio N = number of cycles f = frequency C_p= Coefficient Q = shape factor $2c_{cr}$ = critical pit diameter σ_a = stress amplitude $(\Delta K)_p$ = stress intensity factor
Daidola(1996) *Pitting of Plate Panels in Ship Structures*	$\Delta t = V/A$ $V = c\cdot \sum_{i=1}^{N} ((\pi/4) w_i^2\cdot d_i))$	Δt = thickness reduction due to Pitting V = Wasted Steel Volume A = Area of Plate c = .667 for semi-spherical pits w = pit width d = pit depth
Melchers(1999) *Empirical Model*	$d_w = .084t^{.823}$	d_w = Depth of Corrosion Wastage t = time
Guedes Soares & Garbatov (1999b) *Non-linear model with Three Stages of Corrosion Behavior*	General Equation: $d_\infty \dot{d}(t) + d(t) = d_\infty$. Solution: $d(t) = 0$ for $t > \tau_c$ $d(t) = d_\infty(1- e^{-(t-\tau_c/\tau_t)})$ for $t \leq \tau_c$	d = depth of corrosion d_∞ = long term thickness loss due to corrosion τ_c= time that the coating is effective τ_t = time of transition τ_c = time of corrosion stage t = time
Paik (2003) *Non-linear model with Three Stages of Corrosion*	1) $t_r = C_1(T-T_c-T_t)^{C_2} = C_1T_e^{C_2}$	r_r = annualized corrosion rate T = Structure Age

Behavior	2) $r_r = C_1\, C_2 T_e^{C_2-1}$	T_c = Time of Coating Durability T_t = Transition Time and T_e = Time of Exposure C_1 = constant (indicates annual corrosion rate) C_2 = constant (indicates corrosion process trend) t_r = depth of corrosion
Moan(2004) *Two stage linear corrosion model*	$W(t) = R_{corr} \cdot \alpha(t-T_o)$	W(t) = corrosion wastage α = number of sides exposed = (1 or 2) T_o = time to corrosion protection system breakdown R_{corr} = the annual wastage rate. t = time

The three stage model for corrosion behavior is shown in Figure 7.1 below. The first Stage I is the time until the corrosion protection breakdown, followed by Stage II as a transitional stage, and finally stage III (long term steady state) corrosion.

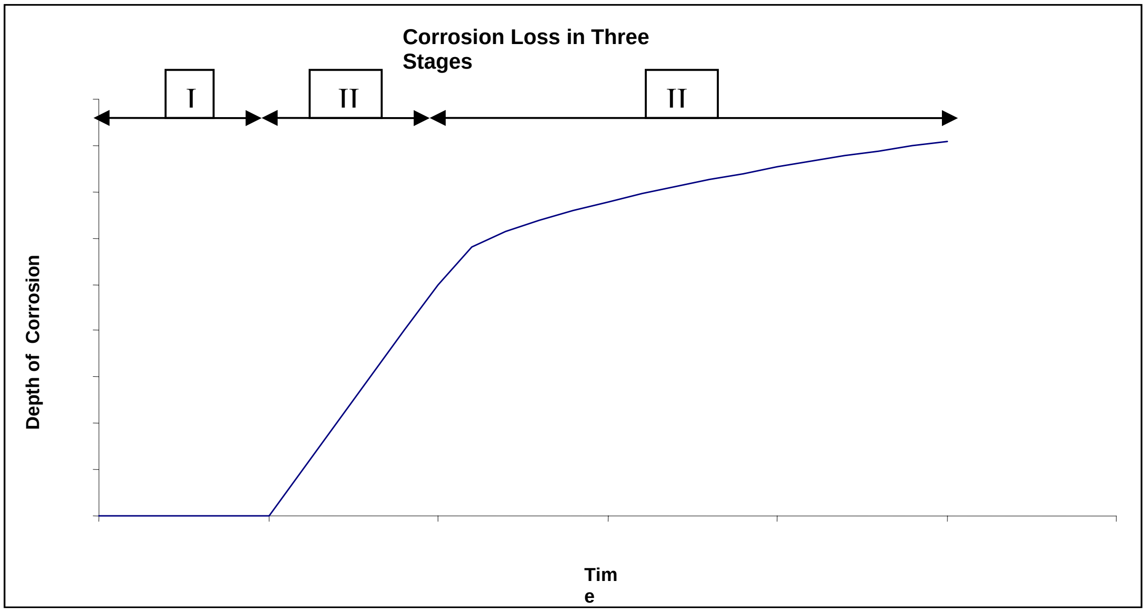


Figure 7.1: Corrosion Behavior as Three Stages

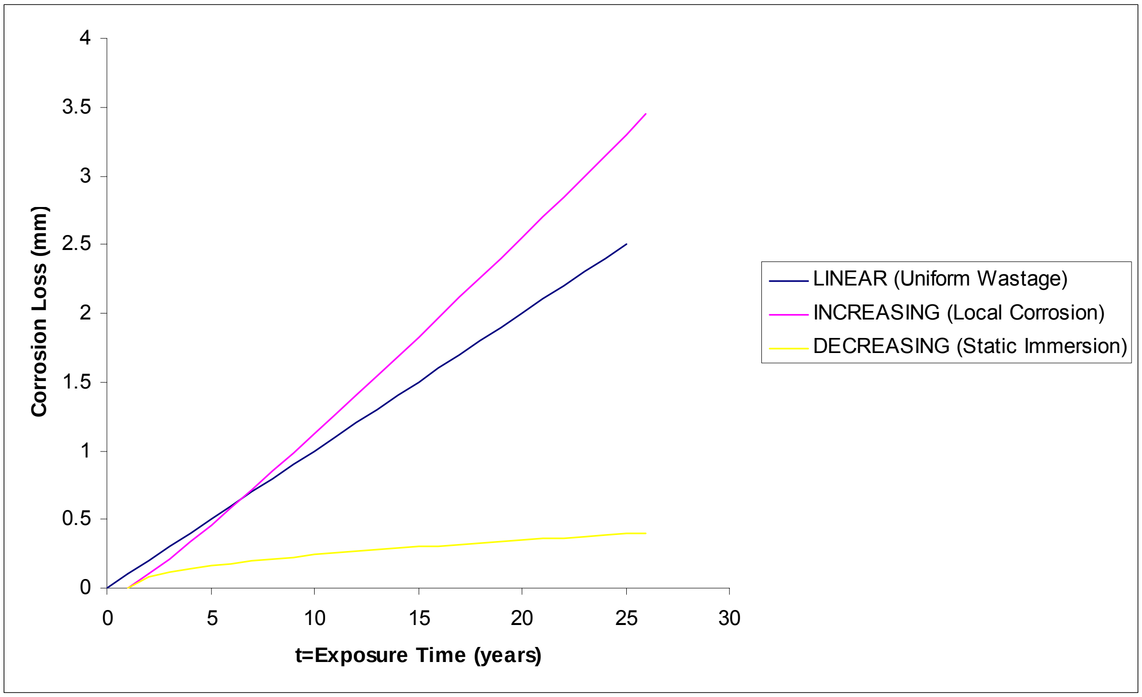


Figure 7.2: Long Term (Stage III) Corrosion Behavior

A comparison of the formulations is shown in Figure 7.2. The graphs shown are for 1) linear behavior of .1mm/yr, 2) decreasing rate that is typical of static immersion, in this case shown using the Melchers equation and 3) increasing rate, using the Paik equation with a coefficient of C_2> 1.

7.4 Corrosion Considerations for Welded Doubler Plates

7.4.1 Mechanisms of Corrosion at Welded Doubler Plates

Corrosion in the area of a welded doubler plate does not have the same mechanisms as that of the base plate material. A primary consideration in corrosion behavior of doubler plates is at the weld and the adjacent HAZ (heat affected zone). The variables associated with the high local corrosion in the area at the weldment is due to the metallurgical differences as well as the higher stresses present. Also, as corrosion occurs, it results in the loss of material and magnitude of stress increases over time. In the case of a doubler repair, the presence of defects and the potential for crevice corrosion as well as pitting are also of concern. The presence of defects includes existing defects as well as cracking due to fatigue is this area. General wastage of the plate should be considered, however the more severe corrosion mechanisms should govern in estimating corrosion loss. The various mechanisms of corrosion of welds are overviewed by Griffiths and Turnbull (1999), in addition to detailing various methodologies for testing. Variables that affect corrosion behavior are listed in Table 7.2.

Table 7.2: Variables of Corrosion Behavior

General Factors Affecting Corrosion Behavior in Marine Environment
Total Immersion vs. Atmospheric or Alternating Wet/Dry Environment Seawater chemistry Oxygen content Temperature Velocity Parent Alloy Corrosion Protection: Coating / Cathodic Protection System MIC (Microbial Induced Corrosion)
Additional Corrosion Considerations at Doubler Plate
Location of Doubler Plate Fatigue Loading Stress Concentration Geometry Profile of Doubler Presence of Residual Stresses at Weldment Presence of Weld Defects Intermittent Welding vs. Continuous Welding Welding Process/Filler Metal /Procedure Used Galvanic Corrosion due to Microstructural Differences at Weldment Localized Corrosion Behavior: Pitting / Grooving / Crevice Corrosion

The higher stresses at the doubler plate due to geometric stress concentration are detailed in the prior sections of this report as being highest at the weld toe. Additional stress concentration occurs in the area of weld defects. Residual stresses are also present due to welding. The welding process and geometry determines the magnitude and type of residual stresses present. These residual stresses exist as a result of constrained thermal expansion/ contraction due to the very large temperature differential of the welding process, as well as by the microstructural changes that occur. The microstructural changes may include multiple phases that are not present in the base plate as well as an altered grain structure. The resultant microstructure and residual stress due to welding are determined by the weld process, heat input, welding speed, weld sequence, joint geometry, heat transferability, and filler metal. Detail of weld metallurgy is by Linnert (1965) and Masubuchi (1980)

The effect of defects present on corrosion and fatigue was discussed in El-Gammal (2003) in the context of a fitness of service approach to optimize fabrication methods. Paik (2003a) also noted that the weld metal corrosion for ship structures was more prevalent for hand welds than for machine welds. This is associated with the more variable quality of hand welding to include more non uniformity and ridges that provide future sites for initiation of corrosion and fatigue behavior. It can be assumed that there may also be a greater presence of weld defects. This observation is important in the consideration of doubler plates, since the welding performed by hand.

Sephon and Pistorius (2000) discuss the specific mechanisms of corrosion of carbon steel weldments tested in flowing 3.5% NaCl. Corrosion rates were determined using electrochemical methods. The difference in potential (mV) was found for different microstructures. It was reported that this galvanic difference between the microstructures was initially the significant corrosion mechanism until steady state conditions were reached. The most significant long term corrosion loss was found at the fusion line of the weld as grooving. The grooves were characterized to consist of a multitude of pits of various depths that appeared to coalesce. In this case the localized corrosion was related to defects of network of sulfide inclusions along grain boundaries. The description of coalesced pitting along the fusion line is consistent with the behavior that has been observed in the corrosion of ship structures in the area of welds having localized pitting / grooving behavior as shown in Stambaugh and Knecht (1988).

Consideration of materials and welding is particularly important in the case of higher strength steels which are susceptible to stress corrosion cracking (SSC) along grain boundaries, particularly in the area of weldments. Additionally, the use of higher strength steel requires less thickness of plate, which results in 1) greater deflection which removes protective scale formation or biofilm, and 2) reduced thickness due to corrosion occurs as a greater percentage of the plate. Additionally, as SSC occurs, the material is embrittled, such that fatigue cracking is accelerated, particularly as the mean stress and stress amplitude is increased. Several studies have discussed the behavior of high strength steels, which is not considered here for doubler plate repairs.

It should be noted that corrosion fatigue is not the same as stress corrosion cracking. Corrosion fatigue is a general condition in that the endurance limit of a metal is lower in a corrosion environment and does not necessarily involve embrittlement. Typically steels have a fatigue limit in air, but do not in an aqueous electrolytic environment. (Talbot, 1998) As the stress is increased, the time until failure is decreased. As the area of a welded repair is at a higher stress level, it is therefore more susceptible to long term fatigue damage. Surface weld defects and pits are also a factor involved with corrosion fatigue in that they provide initiation sites for crack propagation.

Crevice corrosion occurs due to the change in oxygen present in a corrosion environment due to having electrolyte (stagnant seawater) trapped and maintained in a small space. Lapped joints are subject to crevice corrosion which has very accelerated corrosion rates, as the reactivity is high in a small area in which the anodic portion corrodes rapidly. It is key that doublers be watertight to avoid crevice corrosion and also to avoid lack of fusion weld defects.

Pitting has similarities to crevice corrosion in that it is autocatalytic and has high localized rates. Pitting is associated local variations that may become micro-anode / cathodic areas. Mild steels are not susceptible to pitting, however in the case of being in the area of a weld and having stagnant seawater environment, it does occur. An example is that of an internal tank bottom plate which is particularly susceptible to pitting.

A major consideration for the corrosion of doubler plates is the location of the installation. The location is most significant as to whether the doubler repair is for an internal or external location and more importantly if the location environment is in a 1) immersed, 2) atmospheric, or the worst case, 3) an alternating wet / dry condition. For internal repairs exposed to product, the chemistry of the corrosion reaction may be affected, which is not considered here. The location of the doubler also defines the local stress condition.

A further consideration is that the doubler plate repair discussed in this report is to repair prior corrosion damage. The doubler plate repair is therefore at a location that has already been established as a higher corrosion environment that has experienced corrosion protection failure. This serves as additional justification to assume higher corrosion rates in this area and that the time of protection/ transition prior to corrosion behavior is minimal.

7.4.2 Shipyard Survey

A survey of shipyards was conducted for this report in 2004 on the methodology and results of doubler plate application. Of thirteen respondent shipyards, there were varied responses on the approach to doubler repairs which impact corrosion behavior over the lifetime of the doubler plate repair.

The survey conducted reported various applications of doubler plates at different shipyards. The sizes ranged from 3”diameter to 8’x40’. The weld procedures used included both SMAW “stick” (6011 and 7018 filler rods) and MIG welding techniques, heat treatment was not used (with exception of one shipyard that stated heat treatment was seldom used). Varied locations of doublers were reported to include internal and external applications and above and below the waterline. It was noted by two shipyards that doublers were not used for cargo and fuel tank boundaries (this is not allowed by classification societies due to possible entrapment of flammables). One shipyard commented that the doublers were never used in wet spaces although another respondent used doublers for “wet spaces / internal” locations. The lifetime expectation of the doubler repair varied from until “next docking” to “for life”. The results were evenly divided on the question of lifetime, with six respondents stating that the lifetime expectation was from 10 years to life, four respondents had short life time expectations (<2.5 years) and two shipyards did not respond. Since the majority of respondents have an expectation that the doubler repair should have a significant lifetime, the corrosion loss should be known such that premature failure does not occur.

In considering the results of the shipyard survey, most are consistent with the recommendations of the Repair Standard 47 by IACS (1996) for the installation of doublers, with the exception that some of the repairs are smaller that the standard includes. The minimum size doubler plate per IACS is 300mm x 300 mm (11.8 in x 11.8 in). The thickness of the doubler plates ranged from ¼” to 1 inch. All of the shipyards responded that they provided a radius at the corners of the doubler to reduce stress concentration. A 3” radius was the typical dimension given by the respondents, and all of those providing dimensional information exceeded the IACS recommendation of a minimum radius of $R \geq 50$ mm (1.96 inch). The majority of the shipyards used slot welding with size of slots ranging from the width of 1t (thickness of doubler) to 2" diameter (plug) weld, and the length from 1"-3", with some respondents noting the slot was to be completely filled. The slot sizing of the width was generally smaller that in the IACS dimensions of 2t x (80 – 100) for width by length (mm) respectively.

On the use of doubler plates, ten of the shipyard respondents recommended the use of doublers, although two stated that this was for temporary repairs only. Additionally two shipyards did not recommend the use of doubler plates but recommended inserts instead.

Of interest is that two of the shipyards included comments on cracking as 1.) "cracks in parent plates as doubler is applied" and 2.) 'Sometimes cut ' X ' in plate before welding edges - prevents cracking". This substantiates the significant increase in local stresses on the application of the doubler plate. There were several comments on the criticality workmanship, that to be effective the doubler must be installed correctly. There were also several positive comments including those on productivity of being low cost and time-savings as well as "never seen one fail". With the diversity of responses that were given for varied parameters, further guidance on the application of doublers is needed.

7.4.3 Corrosion Behavior of Doubler Plates

As detailed in section 7.4.1, the corrosion behavior in the area of the doubler repair is expected to differ from that of the base plate material and in fact is expected to occur at a higher rate. To quantify the loss due to corrosion in this area, the behavior should be modeled as non-linear behavior that attempts to characterize the particular corrosion mechanism. The approach presented here is to modify a non-linear multiple stage relationship similar to those that have been used on ship structures with coefficients fit to incorporate the higher rate for localized corrosion behavior in the area of the doubler plate.

As detailed it has been seen in several studies that corrosion behavior is not constant, but that it may be generalized into stages. In this case, the three stages approach is used of:

Stage I: t_c= time until corrosion protection system failure
Stage II: t_t= transitional time
Stage III: t_c= time of long term non-linear corrosion behavior

The equation used is in the form of Paik (2003):

$$d = C_1(t)^{C_2}$$

in which the terms are defined as:

d= depth of corrosion (mm)

C_1 = constant (indicator of the corrosion rate)
C_2 = constant (indicator of the corrosion trend)
t = time (year)

For prediction of doubler plate corrosion behavior, the equation is stated as:

Stage I : $d = C_1(t)^{C_2}$, $C_1 = 0$
Stage II: $d = C_1(t\text{-}t_I)^{C_2}$, $C_1 \neq 0$, $C_2 = 1$
Stage III: $d = C_1(t\text{-}t\text{-}t_{II})^{C_2}$, $C_1 \neq 0$, $C_2 \neq 0$

In the use of doubler, Stage I is minimized or may be assumed zero, since this is a repair application such that the original corrosion protection system is not intact and, specifically, the application is for an area that has already failed in corrosion. Additionally the vessel is generally an older vessel, which typically has higher rates of corrosion in part because the aging of the protection system.

The stage II is shown linearly as a higher corrosion rate that then levels off in Stage III non-linear long term corrosion. In this case the galvanic mechanism in the area of the weldment is considered as the driver of the increased corrosion rate in the short term Stage II.

The Stage III corrosion is characterized by the non-linear increasing behavior as the long term corrosion is higher than general wastage due to the fact that this is a higher stress area and to include consideration of localized corrosion. Stage III should not be considered linear general wastage and it also in not suitable to have the decreasing trend typical static immersed system. It is assumed that the location under non-static stress conditions therefore and would not be expected to form a protective film.

A plot of the predictive model is shown in Figure 7.3 using the following:

Region I = 0
Region II ($0 \leq t < 2.5$ years): $C_1 = .5$, $C_2 = 1$ (linear)
Region III ($t > 2.5$years): $C_1 = .05$, $C_2 = 1.03$ (increasing)

The selection coefficients for the figure shown are indicative of the general trend to include general wastage with localized corrosion for doubler plates. The actual rate of corrosion is dependent on the location and the service conditions for the application of repair. Due to the variability as indicated in the studies by Paik, Garbatov, Guedes-Soares and Wang, the location of the doubler is key. Corrosion behavior in general and the lack of continuity of the repair methodology does not lend itself to a particular rate. However, to should be recognize that corrosion rate is higher for a doubler and the localized corrosion increases over time. Recommendations to decrease the more severe corrosion mechanisms in the area of doubler plates are made in the next section.

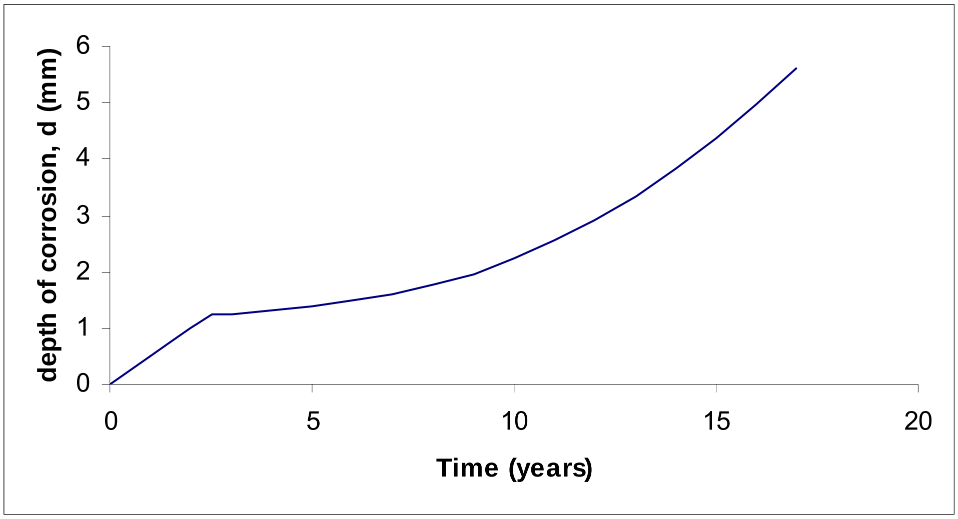


Figure 7.3: Predictive Corrosion Behavior of Doubler Plate Repair

7.5 Recommendations

Recommendations to extend the life of doubler repairs are given as follows based on the respondent shipyard practices and in consideration with factors that increase the corrosion rates:

It is recommended that shipyards to follow the guidelines in IACS 47 (1996) Repair Standard Section 6.3 on doublers. The exception being for those doubler repairs that are smaller than 12” x 12”, which are not covered by the standard. Use a proper welding sequence (i.e. weld opposite sides instead of adjacent sides) as an insert. This reduces the localized stress and therefore the long term corrosion and corrosion fatigue susceptibility. Using rounded corners to reduce stress concentration with a minimum radius of curvature of 2” - 3” is recommended.

In general, avoid the used of intermittent welds, if possible, to avoid localized corrosion to include crevice corrosion. Intermittent weld should only be used in the case of very large doublers. If intermittent welds are found to be necessary, the slot width should be per the guidelines of a minimum of $2t_d$ = twice the doubler plate thickness and the minimum distance of $15t_d$ for a slot to the edge of a plate. Presently, some of the respondent shipyards use more narrow slots, which should be avoided.

As doubler plates are applied by hand and may have great variability in the welding technique, the importance of good welding practices cannot be overemphasized. In the case of doubler repairs, defects that present potential for future corrosion and fatigue sites must be eliminated by grinding and in particular, discontinuity in the toe region of the weld should be avoided. Cracking is not acceptable. Table 3.2 of SSC-400 (Kirkhope, et al., 1996) provides an overview of effective techniques for weld improvement to include hammer peening as well as correct weld profile that are applicable for doubler plate application.

8.0 DESIGN GUIDELINES FOR DOUBLER PLATE REPAIRS

In sections 5 and 6, finite element analyses were performed to check the effect of different doubler plate design parameters on the buckling strength and fatigue strength of stiffened plate panels, respectively. Several recommendations were made based on these analyses. Each set of recommendations was based on the analysis performed with certain variables. In this section, we combine all of the recommendations made in the sections 5 and 6 and come up with one set of recommendations that satisfies all the requirements. Recommendations for reducing corrosion of welded doubler plates were made in section 7.5.

Recommendations made in the previous sections are repeated below for better understanding.

8.1 Doubler Recommendations for Buckling Strength

Based upon the analyses completed and the results that were generated, the following recommendations for restoring the buckling strength of a stiffened plate with a doubler are presented:

- For metal loss greater than 25% of parent plate thickness, the use of doublers is not recommended.
- To restore the buckling resistance of a stiffened panel, the doubler plate thickness should be greater than the larger of:
    - 65% of the original stiffened panel plate thickness ($D_t > 0.65*B_t$)
    - thickness required by the doubler thickness factor of 2.6 (i.e. $2.6*(B_t - C_t)$)
- The doubler size (length and width), and doubler plate edge distance can be any value but care should be taken to minimize the size of the doubler plate. It is recommended that a 50mm (2 inch) corrosion feature to doubler edge distance be used. It is noted that larger doubler plates will need slot welds to ensure stability.

8.2 Doubler Recommendations for Fatigue Strength

8.2.1 Recommendations for Doubler Corner Radius

Based upon the results, a simple linear regression was performed to obtain a relationship between doubler corner radius (D_R), doubler plate thickness (D_t) and base plate thickness (B_t). This relationship is shown below:

$$D_R = 82.4*(D_t / B_t) + 2.46$$

where R has units of mm. This equation may be used to define the most appropriate doubler corner radius for a range of plate thicknesses.

8.2.2 Recommendations for Doubler to Base Plate Thickness Ratio

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Doubler, D_t , thickness should always be greater than $0.5*B_t$
- Doubler thicknesses, should be as large as reasonable
- Doubler to corrosion edge distance should be kept as small as possible and certainly be less than 100 mm

8.2.3 Recommendations for Slot Welds

Based upon the analyses completed and the results that were generated, the following recommendations for maximizing the fatigue life of a doubler applied to a stiffened panel are presented:

- Slot welding on large doubler plates is recommended for corroded stiffened panel.
- Increasing the number of rows of slot weld along doubler width would strengthen the corroded stiffened panel; however, this increases the number potential fatigue crack initiation sites.
- For doubler size and thickness, recommendations from Section 8.2.2 should be followed.

The IACS Guidelines for Temporary Doubler Plate Installation shown in Figure 3.1 is repeated in Figure 8.1.

8.3 Recommendations for Reducing Corrosion

Recommendations to extend the life of doubler repairs are given in section 7.5 and reproduced below.

- It is recommended that shipyards follow the guidelines in IACS 47 (1996) Repair Standard Section 6.3 on doublers. The exception being for those doubler repairs that are smaller than 12” x 12”, which are not covered by the standard.

- For insert plates use a proper welding sequence (i.e. weld opposite sides instead of adjacent sides). This reduces the localized stress and therefore the long term corrosion and corrosion fatigue susceptibility.

- Using rounded corners to reduce stress concentration with a minimum radius of curvature of 2” - 3” is recommended.

- In general, avoid the used of intermittent welds to avoid localized corrosion to include crevice corrosion. Intermittent weld should only be used in the case of very large doublers. If intermittent welds are found to be necessary, the slot width should be per the guidelines of a minimum of $2t_d$ = twice the doubler plate thickness and the minimum distance of $15t_d$ for a slot to the edge of a plate. Presently, some of the respondent shipyards use more narrow slots, which should be avoided.

- As doubler plates are applied by hand and may have great variability in the welding technique, the importance of good welding practices cannot be overemphasized. In the case of doubler repairs, defects that present potential for future corrosion and fatigue sites must be eliminated by grinding and in particular, discontinuity in the toe region of the weld should be avoided. Cracking is not acceptable. Table 3.2 of SSC-400 (Kirkhope, et al., 1996) reproduced below, provides an overview of effective techniques for weld improvement to include hammer peening as well as correct weld profile that are applicable for doubler plate application.

8.4 Final Recommendations

8.4.1 Extent of Corrosion

Most classification societies allow structural diminution of up to 20%, as shown in Table 3.1. However, if the doubler is required to restore the strength of the structure, for risk-mitigation purposes, it is proposed that the doubler plate be used to repair damages when corrosion is less than 25% of the original plate thickness. The existing naval practices also suggest replacing the plate if the corrosion damage is more than 25% of the thickness of the original plate.

Based on these criteria the following recommendation regarding the maximum extent of corrosion is made:

The doubler plates should be used for repair where damage is less than 25% of the parent plate thickness, i.e.

$$B_t - C_t \leq 0.25\ B_t$$

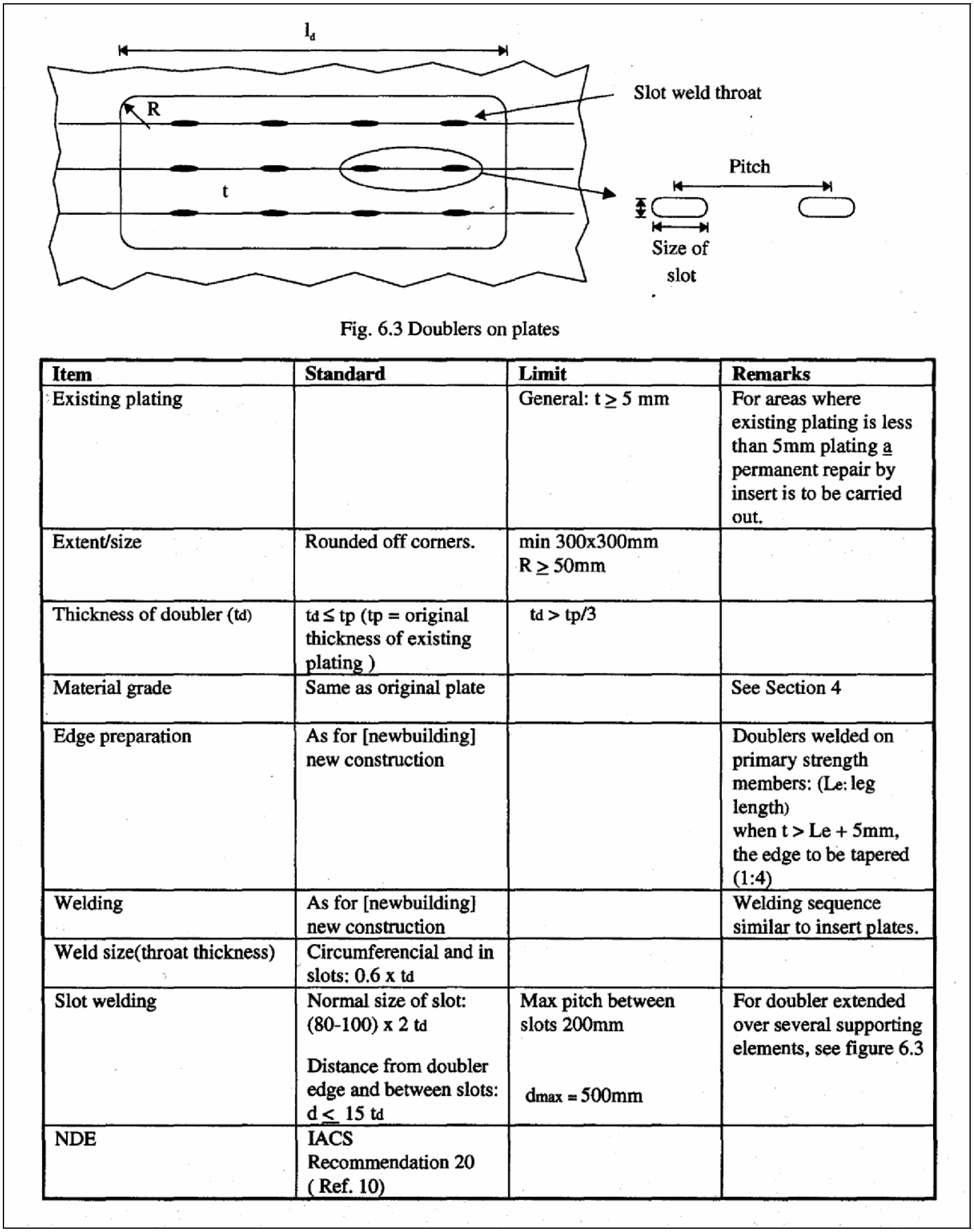


Fig. 6.3 Doublers on plates

Item	Standard	Limit	Remarks
Existing plating		General: t ≥ 5 mm	For areas where existing plating is less than 5mm plating a permanent repair by insert is to be carried out.
Extent/size	Rounded off corners.	min 300x300mm R ≥ 50mm	
Thickness of doubler (td)	td ≤ tp (tp = original thickness of existing plating)	td > tp/3	
Material grade	Same as original plate		See Section 4
Edge preparation	As for [newbuilding] new construction		Doublers welded on primary strength members: (Le: leg length) when t > Le + 5mm, the edge to be tapered (1:4)
Welding	As for [newbuilding] new construction		Welding sequence similar to insert plates.
Weld size(throat thickness)	Circumferencial and in slots: 0.6 x td		
Slot welding	Normal size of slot: (80-100) x 2 td Distance from doubler edge and between slots: d ≤ 15 td	Max pitch between slots 200mm dmax = 500mm	For doubler extended over several supporting elements, see figure 6.3
NDE	IACS Recommendation 20 (Ref. 10)		

Figure 8.1: IACS Guideline for Temporary Doubler Installation

8.4.2 Doubler Thickness

Based on the buckling strength analysis, the thickness of doubler plate was recommended to be more than 65% of the thickness of the parent plate. Based on the doubler thickness factor, the thickness of the doubler plate should be

$D_t \geq 2.6 * (B_t - C_t)$

In section 8.3.1, it is assumed that the maximum corrosion is 25% of the parent plate, i.e.

$B_t - C_t = 0.25 B_t$

Combining the above two equations, we get

$Dt \geq 0.65 * Bt$

Based on the fatigue strength analysis, the thickness of the doubler plate should be at least half the thickness of the base plate (i.e. $Dt \geq 0.5* Bt$). The fatigue analysis also indicated that thicker doubler plates provide better fatigue strength.

Based on the above discussion, the thickness of the doubler plate is proposed as:

The thickness of the doubler plate should be more than 65% of the thickness of the parent plate, i.e.

$$D_t \geq 0.65 * B_t$$

The minimum doubler thickness recommended by IACS guidelines is $B_t/3$.

8.4.3 Doubler Corner Radius

Based on the survey of shipbuilders/ship-owners, most use doubler corner radius between 2 – 3 inches. IACS guidelines for doubler plate suggest minimum radius of 50 mm (2”). The equation for the doubler corner radius based on the regression analysis was obtained as

$$D_R = 82.4*(D_t / B_t) + 2.46$$

If $D_t = B_t$, then $D_R = 84.86 \approx 85$ mm. To make the equation for doubler corner radius simpler, the following expression is proposed:

$$D_R \geq 85*(D_t / B_t)$$

This equation also meets the minimum specified by IACS Rules. From the recommendation made in section 8.4.2,

$Dt/Bt \geq 0.65 \Rightarrow D_R \geq 55$ mm.

8.4.4 Overlap

Based on the results from the buckling analysis, the overlap between the doubler plate and the corroded patch was proposed as 50 mm (2"). Based on the fatigue analysis, the overlap was recommended to be as small as possible but less than 100 mm (4"). The proposed overlap for the doubler plate design is as follows:

$50 \text{ mm} \leq O_L, O_W \leq 100 \text{ mm}$

O_L - Length of overlap (Edge Distance) = ½ *($B_L - C_L$)

O_W - Width of overlap (Edge Distance) = ½ *($B_W - C_W$)

8.4.5 Slot Welds

As shown in section 6.3, the slot welds were found to be effective in reducing the hot spot stresses. Slot welds applied along the stiffeners were found to be most effective in reducing hot spot stresses. However, we have to keep in mind that slot welds may also introduce potential fatigue crack initiation sites. Based on the analyses performed during this study, it is proposed that

Slot welds should be used for large doubler plates and if possible, should be along the stiffeners.

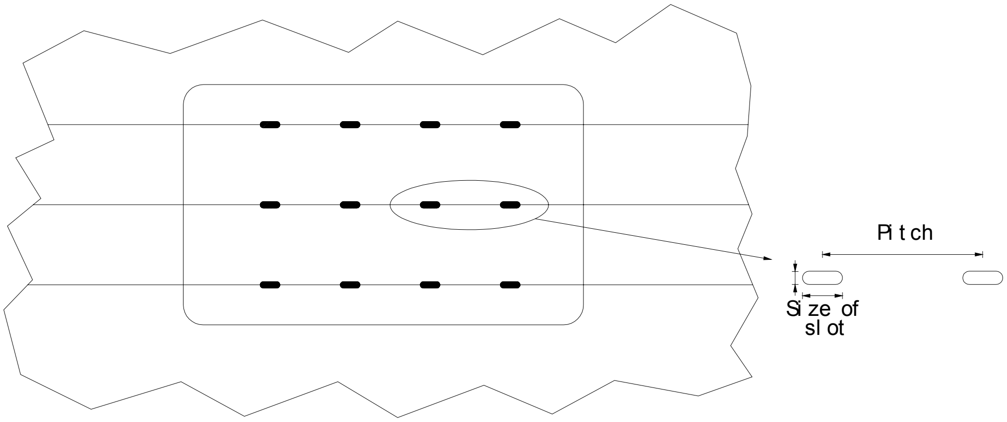
8.4.6 Weld Sizes and Edge Preparation

The effects of weld sizes and edge preparation on the fatigue strength of doubler plates were not analyzed in this study and could be a topic for future studies. The recommendation given in IACS guidelines regarding weld sizes and edge preparation are proposed.

8.4.7 Corrosion

It is recommended that shipyards follow the guidelines in IACS 47 (1996) Repair Standard Section 6.3 on doublers. The doublers that are smaller than 12” x 12”, and are not covered by IACS should follow good welding practices. Slot welding should be minimized as far as possible. Weld improvement techniques such as back grinding or hammer peening should be used.

These recommendations are also tabulated in Figure 8.2 in the same format as IACS recommendations shown in Figure 8.1.



Item	Standard	Limit	Remarks
Minimum Damage Thickness (C_t)		$C_t \geq 0.75 * B_t$	No IACS Recommendations
Doubler Thickness (D_t)		$\geq 0.65 * B_t$	IACS recommends $\geq 0.33 * B_t$
Overlap (S)		$50 \leq O_L,O_W \leq 100$ mm	No IACS Recommendations
Doubler Corner Radius (D_R)	Rounded off corners	Greater of : $D_R \geq 50$ mm (2”) or $D_R = 85 (D_t/B_t)$	IACS recommends $D_R \geq$ 50 mm (2”)
Material Grade	Same as parent plate		IACS Recommendation
Edge Preparation	As for new construction	Doublers welded on primary strength member (Le=leg length): When t > Le + 5 mm, the edge to be tapered (1:4)	IACS Recommendation
Welding	As for new construction		IACS Recommendation
Weld Size (throat thickness)	Circumferential and in slot: $0.6*D_t$		IACS Recommendation
Slot Welding	Normal size of slot: (80 to 100) x 2 D_t Distance from doubler edge and between slots: $d \leq 15 D_t$	Max pitch between slots 200 mm $d_{max} = 500$ mm	IACS Recommendation
Large Doubler			Align slot welds with stiffeners.

Figure 8.2: Guidelines for Doubler Plate Repairs

9.0 CONCLUSIONS

This project has developed guidelines for performing repair work on ship structures using doubler plates. The guidelines were developed based on the responses received from several ship-owners, shipbuilders and classification societies during personal interviews and also using the results from finite element analyses performed to check buckling and fatigue strength of doubler plates. These guidelines were developed so that the damaged structure regains its original strength with the addition of the doubler plates and the repairs are considered permanent.

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APPENDIX A: SHIPYARD AND SHIP OPERATOR QUESTIONNAIRE

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Shipyard Call Intro

- Personal Intro – Name and Company
- Explain that D&P is a Naval Architecture firm
- Explain we are performing a study on behalf of the Ship Structures Committee
- Mention "as you may know the SSC is a multi-agency board representing US and Canadian shipbuilding that funds studies by industry to investigate and further the status of technology and safety of marine structures"
- Explain that the SSC has tasked us, D&P to investigate the use of doubler plates in the repair of damaged and depleted ship structure.
- Ask if the yard does see doublers on new or repair jobs
- If so, is it possible for us to come and talk to them and discuss their experiences with doublers
- Note that we only take an hour or two of their time
- Mention that all information given to us would be confidential and that nothing would be published in a way that could be traced back to them or the yard
- Tell them they can always refuse to answer any question we ask
- Mention that the results of our study will be available to them through the SSC when it is finished
- Explain that we would like to ask a series of questions about their normal practices and use of doublers.
- We would be especially appreciative of any specific case data that we could get on particular doubler instances
    - Ship characteristics
    - Damage type
    - Doubler characteristics
    - Any follow up data about success/struggles with doublers in service
- If such a visit is possible we would like to come in the next month or two
- Are there any times when they will not be available over the next two months
- Can we get back to them to try to schedule a visit – what times are best for them
- If visit not possible, are they willing to give telephone interview or respond to our questionnaire by email
- Mention that if they would like we can send them an advance copy of the questions that would help them see what we are looking for
- We would be happy to talk to them later personally as well about the findings of the study

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

1. General Info:
   - a. Date:____
   - b. Name of interviewer:____
   - c. Name of shipyard/ship owner: _____________________________________
   - d. Name of interviewee: ____
   - e. Interviewee's email address and phone no.:___________________________

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2. How does the yard use doublers/straps: Repair / New Build / Both
3. If New Build, typical applications: _______________________________________

   ____

   ____

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

   Other / Describe (if possible include probable cause and mode): ________________

   ____

   ____

   ____

   ____

5. What locations:

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

6. Are repairs with doubler ever intended to be permanent? Yes / No ______________
7. What is their expected life span: ____
8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):

   ____

   ____

   ____

9. Does the service of the vessel effect the decision to use doublers: Yes / No
10. If yes, then how:
    a. Cargo type: ____
    b. Waterway: ____
    c. Vessel Route: ____
    d. Seasonal Restrictions: ____
    e. % of time in service: ____
11. What materials are used for doublers, how do they relate to hull material: _________

    ____

12. Typical doubler plate geometry:
    a. Thickness in relation to parent plate:__________________________________

       ____

    b. Min/Max thickness: ____
    c. Min/max overall dimensions: ____
    d. Min/Max aspect ratio: ____
    e. Corner Radii: ____
    f. End Tapering: ____

       ____

    g. Other: ____

       ____

       ____

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc): ________________________

____

____

____

____

____

14. Weld Details:
    a. Are slot welds used: Yes / No
        i. If yes, what is their:
            1. Spacing parallel to stiffeners: _________________________
            2. Spacing in second direction: __________________________
            3. Common slot W x L: ________________________________
            4. Sketch (if desired, use back of sheet):

    b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: ____
    c. Common welding process(es) / procedure(s): _________________________

    ____
    d. Commonly used filler metal types relative to doubler and hull materials:

    ____
    e. Are Pre- or post weld heat treatments commonly used? Yes / No
        i. If yes, please describe them:_________________________________

        ____

        ____
    f. Other prep or post weld details: ___________________________________

    ____

    ____

____

____

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.): ________

____

16. What design criteria is commonly used:

   ____

   ____

   ____

17. Are the doublers approved by a class society: _______________________________

   a. Which one(s): ____

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

   ____

   ____

   ____

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): Yes / No

   a. If yes, were they intended to be temporary or permanent?_____________________________

      ____

      ____

20. Typically how long have you seen doublers last in service: ____________________

   ____

   a. What is the oldest seen:____

21. What is the condition of a typical doubler after its service life?

   ____

   ____

   ____

a. Are there usually signs of fatigue or fracture? Yes / No
    i. If so, please describe: ______________________________________

    ____

    ____

    ______

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No
    a. If so, please describe____

    ____

    ____

    ____

    ____

    ____

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers?: ____

    ____

    ____

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe: ____

    ____

    ____

    ____

    ____

    ____

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: Yes / No

    a. Please expand on reasoning:___________________________________

    ____

    ____

    ____

    ____

    ____

26. Notes: ____

____

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APPENDIX B: SHIPYARD AND SHIP OPERATOR QUESTIONNAIRE RESPONSES

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Shipyards and operators are identified numerically as they wish their responses to be anonymous.

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: May 13, 2004
   b. Name of interviewer: Lynne Jay and Malcolm Willis
   c. Name of shipyard/ship owner: Company 1
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

30%

4. If Repair, what types of damage: [✓ Local wastage] / [✓ Pitting] / [✓ Cracks] / Local Buckling

Other / Describe (if possible include probable cause and mode):

Drill and weld cracks; doubler over it.

5. What locations: Deck and freeboard mostly above waterline

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	Use doublers everywhere, including flanges To add strength and replace deteriorated material				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No
7. What is their expected life span: Same as painting, up to 15 years

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
Ferries, cargo ships, barges, tugs, no Navy ships

9. Does the service of the vessel affect the decision to use doublers: Yes / [✓ No]

10. If yes, then how:

a. Cargo Type:
b. Waterway:
c. Vessel Route:
d. Seasonal Restrictions:
e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
Match the base material

12. Typical doubler plate geometry:

a. Thickness in relation to parent plate: Back to good structure - overlap two feet of bad hull – replace lost material
Minimum ¼ inch; ½ inch most common, up to ¾ inches
b. Min/Max thickness:
c. Min/Max overall dimensions: 4 ft by 6 ft
d. Min/Max aspect ratio:
e. Corner Radii: Yes
f. End Tapering: Yes
g. Other:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc): Grind away for weld

14. Weld Details:

a. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: ~ 18" to 24"
2. Spacing in second direction: ~ 18" to 24"
3. Common slot W x L: Round slot 2"
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Plate thickness + $^1/_{32}$ inch

c. Common welding process(es) / procedure(s): Flex core, stick weld on old barges

d. Commonly used filler metal types relative to doubler and hull materials: Match base materials; flux core, stainless

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. [✓ shipyard], engineering firm, etc.): Experienced shipfitter

16. What design criteria is commonly used:

____

____

17. Are the doublers approved by a class society: Yes

    a. Which one(s): ABS

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

QA department, visual inspections; SUPSHIP for Navy

____

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

    a. If yes, were they intended to be temporary or permanent?

    Not sure

20. Typically how long have you seen doublers last in service: 15 years

____

    a. What is the oldest seen? 15 years

21. What is the condition of a typical doubler after its service life?

Same as the rest of the hull

____

    a. Are there usually signs of fatigue or fracture? Yes / [✓ No]

        i. If so, please describe: ______________________________

____

____

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No

    a. If so, please describe: ______________________________

Deterioration depends on seal weld. If bad, hull decomposes.

23. What facilities (yard, [✓ dockside service], divers etc.) have been used to install the temporary doublers?

24. Have any unusual geometry or welding schemes been encountered: Yes / [✓ No]
    a. If so, please describe: Rectangular with rounded corners

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning:

    If properly done, cost savings, good service, no problems.

26. Notes:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: May 12, 2004
   b. Name of interviewer: Lynne Jay and Malcolm Willis
   c. Name of shipyard/ship owner: Company 2
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

4. If Repair, what types of damage: [✓ Local wastage] / [✓ Pitting] / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Drill and weld cracks; doubler over it.

5. What locations: Wet spaces; internal

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No
7. What is their expected life span: Next overhaul period, about ten years

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
Cargo ships, barges, amphibious ships, combatant ships

9. Does the service of the vessel affect the decision to use doublers: [✓ Yes] / No

10. If yes, then how:

    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
Grade A-36

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate: Commercial up to ¼ inch in general
    Military no real established method
    b. Min/Max thickness: $^1/_4$ inch to $^3/_8$ inch
    c. Min/Max overall dimensions: Cover degraded area, catch stiffeners
    d. Min/Max aspect ratio:
    e. Corner Radii: Yes
    f. End Tapering: No
    g. Other:

13. What surface preparation procedures are commonly performed (i.e. [✓ remove existing paint and corroded material], fair plating to ensure it is flat, etc):

in weld areas

14. Weld Details:

b. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: on longitudinal stiffeners
2. Spacing in second direction: 12 inches both directions
3. Common slot W x L: 1 ft by 2 inches
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: ~ $^3/_{16}$ inch on ¼ inch plate

c. Common welding process(es) / procedure(s): ______

d. Commonly used filler metal types relative to doubler and hull materials: Match base materials; flux core, stainless

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them: ______

f. Other prep or post weld details: ______

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.): Field activity, QA/shipyard

16. What design criteria is commonly used: Experience

17. Are the doublers approved by a class society: SUPSHIP approval
    a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Visual inspections

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No
    a. If yes, were they intended to be temporary or permanent?
       Not sure

20. Typically how long have you seen doublers last in service: Not sure, long periods
    a. What is the oldest seen? Not sure

21. What is the condition of a typical doubler after its service life?
    a. Are there usually signs of fatigue or fracture? Yes / [✓ No]
       i. If so, please describe:

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No
    a. If so, please describe:

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Commercial with divers or on interior

24. Have any unusual geometry or welding schemes been encountered: Yes / [✓ No]
   a. If so, please describe: Rectangular with rounded corners

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
   a. Please expand on reasoning:

   Cost effective repair, lasts in service and quick fix.

26. Notes:

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: May 12, 2004
   b. Name of interviewer: Lynne Jay
   c. Name of shipyard/ship owner: Company 3
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications: N/A

4. If Repair, what types of damage: [✓ Local wastage] / [✓ Pitting] / [✓ Cracks] / Local Buckling

Other / Describe (if possible include probable cause and mode):

Gauge, drill end, weld and double plate over.

on stringers

additional section modulus

5. What locations:

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL	No, per ABS and Lloyds				
Bottom Pl	Belts on shell				

On weather deck, standing water

Stack decks

Flanges on longitudinals or to add strength

If below waterline, can do temporary repair until drydocked for permanent repair

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No Depends on location
7. What is their expected life span: Life of ship

8. On what types of vessels has the yard applied doublers (i.e. [✓ ferries], [✓ cargo ships], etc.):
Barges, containerships, MSC vessels, tugs, tankers, dredges, cruise ships

9. Does the service of the vessel affect the decision to use doublers: [✓ Yes] / No

10. If yes, then how: No Navy

    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
Try to match grade 96% A-36

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate: Try to match unless large quantities; then less is used. Depends on wastage, replace plus a little more.
    b. Min/Max thickness:
    c. Min/Max overall dimensions: 6-inch diameter to very large
    d. Min/Max aspect ratio:
    e. Corner Radii: Yes, 3 inches always
    f. End Tapering: Yes, with thick plating in beef-up cases
    g. Other:

13. What surface preparation procedures are commonly performed

(i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):
Grind away for weld

14. Weld Details:

c. Are slot welds used: [✓ Yes] / No Port engineer determines – on top of stiffeners

i. If yes, what is their:

1. Spacing parallel to stiffeners:
2. Spacing in second direction: < 18", usually 12"
3. Common slot W x L: ¾ to 1 ½ depending on thickness
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: ½ plate thickness + $^{1}/_{16}$ inch, usual plate thickness

c. Common welding process(es) / procedure(s): Stagger weld to prevent warping

d. Commonly used filler metal types relative to doubler and hull materials:
7018 or mig

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates ([✓ i.e. shipyard], engineering firm, etc.):
Engineering department, submit to owner or owner will designate

16. What design criteria is commonly used:

Best marine practice

17. Are the doublers approved by a class society:

a. Which one(s): ABS or Lloyds - visual

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Visual, standing water, water test

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

a. If yes, were they intended to be temporary or permanent?

Both – some designed to be permanent

20. Typically how long have you seen doublers last in service: 10 years

a. What is the oldest seen? Hard to tell

21. What is the condition of a typical doubler after its service life?

Varies – surrounding surfaces could show deterioration or cracks could propogate

a. Are there usually signs of fatigue or fracture? [✓ Yes] / No

i. If so, please describe: Varies

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No

a. If so, please describe: Don’t really remove. If taken off, cut out and do insert. Difficult to remove.

23. What facilities ([✓ yard], [✓ dockside service], [✓ divers] etc.) have been used to install the temporary doublers? Diver screwed on fairwater

24. Have any unusual geometry or welding schemes been encountered: [✓ Yes] / No
    a. If so, please describe: Trimmed to suit unusual shapes, bottom of bulkheads around house.

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning: In certain areas, cost effective. Not on shell, main strength deck, midbody

26. Notes: Doesn’t like to use doublers

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 1, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 4
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

Not much now

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

All for uninspected vessels: Mostly local wastage and pitting, cracks, back gauge

and crack arresting – then strap over – local buckling – only once really attempted to

get vessel to repair

5. What locations: Don't worry about longitudinal position

<table>
<tr><th>Long'l Position/ Structure Type</th><th>Aft Peak</th><th>0.75 L</th><th>Midship</th><th>0.25 L</th><th>Fore Peak</th></tr>
<tr><td>Side Pl Abv WL</td><td colspan="5" rowspan="7">Decks – only for equipment
Most common strips along keel and on bilge
Mostly exterior on shell – on bilge mostly or transition at forward ¼ – mostly wear on plate
Some on internal bulkheads – down low near bottom where there is corrosion</td></tr>
<tr><td>Side Pl Blw WL</td></tr>
<tr><td>Bottom Pl</td></tr>
<tr><td>Major Bhd Pl</td></tr>
<tr><td>Minor Bhd Pl</td></tr>
<tr><td>Shell Stiff web/fl</td></tr>
<tr><td>Other Stiff web/fl</td></tr>
</table>

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes / No

   On small inland vessels, often permanent

   Many put on temporarily, maybe 2-3 years until major overhaul

7. What is their expected life span: ______

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):

   Small uninspected ferries, barges, towboats, seismic crew boats

   Some don't report, but rather wait for next drydocking period

9. Does the service of the vessel affect the decision to use doublers: [✓ Yes] / No

10. If yes, then how:

    a. Cargo Type: ______
    b. Waterway: Mostly inland vessels
    c. Vessel Route: ______
    d. Seasonal Restrictions: ______
    e. % of time in service: ______

11. What materials are used for doublers, how do they relate to hull material:

    Most HTS work is A-36, so use A-36 to match. Very little else seen but would match material – even once on aluminum barge – temporary fix

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate: Try to match parents – up to $^{3}/_{8}$ inch (minimum $^{1}/_{4}$ inch) is what is seen most often
    b. Min/Max thickness: ______
    c. Min/Max overall dimensions: 6 in by 6 in, to whole bottom
    d. Min/Max aspect ratio: Strips 2 inches wide (reinforcing plate)
    e. Corner Radii: Yes (3 inches routine)
    f. End Tapering: Don't need – if use thick one for machinery, then taper

g. Other: Heat, and then beat to fit

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc): Steel is coated, might blast to prepare surface

14. Weld Details:

d. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: Match to stiffeners
2. Spacing in second direction: 2 ft center
3. Common slot W x L: 2 in by ½ in
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Plate thickness + $^1/_{16}$ inch

c. Common welding process(es) / procedure(s): Wire feed or rods, nothing exotic, 7018 rods

d. Commonly used filler metal types relative to doubler and hull materials: Match base materials; flux core, stainless

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them: Only for thick ones under equipment

f. Other prep or post weld details: Generally specified by owner, who designates area, and may give some guidance, but forman does most in yard on-site

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship owner

16. What design criteria is commonly used:

Rule of thumb – in the rare case of installing doublers with Class approval, they create site-specific procedures – agreed upon by local surveyor – sometimes for pressure vessels)

17. Are the doublers approved by a class society: No

   a. Which one(s): ABS

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Normally visual only, and then hydrostatic test (vacuum box or internal press)

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

   a. If yes, were they intended to be temporary or permanent?

   Some are temporary – but how long is temporary? Some are permanent.

20. Typically how long have you seen doublers last in service:

Many are a few years but some last for the life of the vessel (up to 30 years)

   a. What is the oldest seen? Sometimes see doublers on doublers (once 4 layers)

21. What is the condition of a typical doubler after its service life?

Worn and eroded, but not excessively. Not corroded. Never saw failed weld.

Can get fuel between layers – dangerous

   a. Are there usually signs of fatigue or fracture? Yes / No

      i. If so, please describe:

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No
    a. If so, please describe: Doubler closes off area from external air. Fills with corrosion and corrosion and trash, which shuts off air supply.

23. What facilities (yard, dockside [✓ service, divers] etc.) have been used to install the temporary doublers? Divers are rare, but sometimes used. Mostly for temporary repairs. Have ballasted over to expose plate.

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning: In some cases, under proper conditions and with proper guidelines, it could be applied safely. It is not much easier than cropping and renewing, and often is no cheaper. Time is often the driver, doublers are faster. Would prefer to crop and put lapped plate over hole.

26. Notes:

Where plate is too corroded, sometimes cut window in parent near internal structure. Tie back of doubler to stiffener with a clip.

Have seen places where parent plate will crack as doubler is applied – stress of doubler will expose heat-affected zones or flaws, or just weak plate.

Doubler can be much easier in areas of shape, since fitting and shaping insert is difficult

Does not think that doublers ever pay over long haul – will give problems later

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 2, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 5
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: Repair / New Build / [✓ Both]

3. If New Build, typical applications: Machinery foundations, etc.

4. If Repair, what types of damage: [✓ Local wastage] / Pitting / [✓ Cracks] / Local Buckling

Other / Describe (if possible include probable cause and mode):

Wastage, cracks, emergency repairs on commercial tugs

5. What locations: <u>Gave nothing specific</u>

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	Use only for inland vessels				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes / [✓ No]
7. What is their expected life span:

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
   Barges, tugs

9. Does the service of the vessel affect the decision to use doublers: Yes / No

10. If yes, then how: Owner's direction governs

    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
    A-36 – same as parent

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate:
    Based on what is in stock, but at least as thick as parent
    b. Min/Max thickness: $^{1}/_{4}$ in to $^{3}/_{8}$ in
    c. Min/Max overall dimensions: 3 ft by 3 ft smallest, cost driven (smaller makes it hard to earn profit).
    e. Corner Radii: Yes
    f. End Tapering: No
    g. Other:

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):

Burn off paint, maybe power wirebrush – just enough to be able to weld

14. Weld Details:

e. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: Min 12 inches, set on long'l
2. Spacing in second direction: 12 in
3. Common slot W x L: $^3/_8$ in or $^1/_2$ in x 2 (or 3), fill slot
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Normal $^1/_2$ thickness + $^1/_{16}$ inch

c. Common welding process(es) / procedure(s): Normal fillet

d. Commonly used filler metal types relative to doubler and hull materials:

e. Are Pre- or post weld heat treatments commonly used? Yes / No

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):

Shop foreman and vessel owner

16. What design criteria is commonly used:

6 inches and beyond a problem in all directions – experience

17. Are the doublers approved by a class society: No
    a. Which one(s): ABS

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Hose test.

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No
    a. If yes, were they intended to be temporary or permanent?
    Some owners think they are permanent; shipyards think all are temporary

20. Typically how long have you seen doublers last in service: Several years
    a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?
Have seen doublers on doublers, up to seven layers is most interviewee has seen
    a. Are there usually signs of fatigue or fracture? Yes / [✓ No]
        i. If so, please describe:

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No
    a. If so, please describe: Have seen whole range

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Out of water, dockside

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: Yes / [✓ No]
    a. Please expand on reasoning:
    Only good if speed of repair is required, but is not effective over long term

26. Notes:

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348, Design Guidelines for Doubler Plate Repairs of Ship Structures Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 2, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 6
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

30%

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Wastage and pitting – work on shrimp boats.

Undisputed only – location decided by owner.

5. What locations:

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes / [✓ No]
7. What is their expected life span: Short

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):

   Shrimp boats only

9. Does the service of the vessel affect the decision to use doublers: Yes / No

10. If yes, then how:
    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:

    Same as hull

12. Typical doubler plate geometry:
    a. Thickness in relation to parent plate: Same as hull
    b. Min/Max thickness: Never < $^{5}/_{16}$ in – not much thicker since only temporary
    c. Min/Max overall dimensions: Minimum 12 in by 12 in, to whatever needed
    d. Min/Max aspect ratio:
    e. Corner Radii: Yes
    f. End Tapering:
    g. Other: Very important to make sure parent material is good enough to hold doubler.

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):

    Sandblast boat first

14. Weld Details:

    f. Are slot welds used: [✓ Yes] / No

        i. If yes, what is their:

            1. Spacing parallel to stiffeners: On stiffeners ~ 12” to 18”
            2. Spacing in second direction: Same as longitudinal
            3. Common slot W x L: 1 t by 3 inches
            4. Sketch (if desired, use back of sheet:

    b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Normal fillet $^1/_2$ thickness + $^1/_{16}$ inch

    c. Common welding process(es) / procedure(s):

    d. Commonly used filler metal types relative to doubler and hull materials:

    e. Are Pre- or post weld heat treatments commonly used? Yes / No

        If yes, please describe them:

    f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.): Shop foreman

16. What design criteria is commonly used:

17. Are the doubler approved by a class society: No

    a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

    Temporary only, so not much

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

    a. If yes, were they intended to be temporary or permanent?

       Temporary, but usually stay in service for years; see doublers on doublers

20. Typically how long have you seen doublers last in service: 10+ years

    a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?

    Same as the rest of the boat

    a. Are there usually signs of fatigue or fracture? [✓ Yes] / No

       i. If so, please describe: Cracks in pushboats have come through doublers

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No

    a. If so, please describe:

       Some do – depends on how work is performed.

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? All done out of water

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: Yes / [✓ No]
    a. Please expand on reasoning:
    Inserts only – temporary OK but it is typical that once installed, they never come off

26. Notes:
Old oil supply boat – doubled half of bottom, USCG allowed it

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 2, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 7
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

Also uses lap plate (cut away old and lap on plate outside) – does this the most

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Big dings, corrosion, cracks

5. What locations:

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	95% of owners want inserts rather than doublers Barge – on rolled chines Boats – stern corner, corrosion on deck				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No
7. What is their expected life span: Lifetime of vessel

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
   Barges (inland, deck)

9. Does the service of the vessel affect the decision to use doublers: [✓ Yes] / No

10. If yes, then how:

    a. Cargo Type: Tanks are to be …?
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
    Match or slightly exceed the base material. Has done more in aluminum than steel
    Aluminum is less likely to corrode

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate: At least same
    b. Min/Max thickness: $^{3}/_{16}$ inch to $^{1}/_{2}$ inch
    c. Min/Max overall dimensions: 4 inch by 4 inch TO 3 feet by 4 feet
    d. Min/Max aspect ratio: Typically 1.0, but will go more
    e. Corner Radii: Yes, typically 2 to 3 inches
    f. End Tapering: Not usually, thinner doublers don't need end tapering
    g. Other:

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):
Nothing special

14. Weld Details:

g. Are slot welds used: Yes / No Yes for all new build, No for lapped plate

i. If yes, what is their:

1. Spacing parallel to stiffeners: ~ 12 inch spacing
2. Spacing in second direction: ~ 12 inch spacing
3. Common slot W x L: 1 thickness + 3 inches (fill)
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: For smaller ~ $^1/_4$ inch; for larger 1 root +2 extra passes

c. Common welding process(es) / procedure(s): Standard

d. Commonly used filler metal types relative to doubler and hull materials:
7018 – 045 wire

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):
Shop foreman, based on history – use engineer if something new

16. What design criteria is commonly used:

Rule of thumb

17. Are the doublers approved by a class society: No

    a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Always test seal – pressure in tank or local; check if not ....

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

    a. If yes, were they intended to be temporary or permanent?

    Permanent – they tend to stay on

20. Typically how long have you seen doublers last in service:

    Long time – see fireboat discussion under Item 26, Notes

    a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?

    Typically worse than original because paint has been done poorly and corrosion is bad

    a. Are there usually signs of fatigue or fracture? Yes / [✓ No]

        i. If so, please describe:

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No

    a. If so, please describe:

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? On marine rail, dockside, roll vessel to expose area below waterline

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe: Have seen with round and square corners, sometimes with both simultaneously

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: Yes / No
    a. Please expand on reasoning: In some applications, YES. If properly installed and maintained, they perform well. Still thinks inserts are best.

26. Notes: Local fireboat – 50+ years lap plate and doublers all over

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
    a. Date: June 2, 2004
    b. Name of interviewer: Dan Gallagher and Malcolm Willis
    c. Name of shipyard/ship owner: Company 8
    d. Name of interviewee:
    e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: Repair / New Build / [✓ Both]

3. If New Build, typical applications:

New – pillar, machinery and wear plates

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Don't use in fuel tanks; tend to use inserts rather than doublers

Use on own stuff – wastage

5. What locations: Deck and freeboard mostly above waterline

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	Mostly internal except wear plate Closing plates on struts Compensation for bulkhead and girder penetration				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No
For both new build and repair

7. What is their expected life span: Same as for hull

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
Supply boats, tugs, floating casinos, fishing boats for North Sea

9. Does the service of the vessel affect the decision to use doublers: Yes / [✓ No]

10. If yes, then how:
    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:
Same as for hull

12. Typical doubler plate geometry:
    a. Thickness in relation to parent plate: Wear plates 2 x parent, case dependent
    b. Min/Max thickness: ¼ inch to 1-½ inch
    c. Min/Max overall dimensions: 8 ft by 8 ft TO is as small as we can make
    d. Min/Max aspect ratio: Case dependent
    e. Corner Radii: Usually – L/8
    f. End Tapering: If classed, edges are tapered
    g. Other:

13. What surface preparation procedures are commonly performed

(i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc): Chip rust off

14. Weld Details:

h. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: 12" to 12" grid max, but try to align with stiffeners
2. Spacing in second direction:
3. Common slot W x L: 1.5 t is width; 1" to 3" length
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Often fill up plug – fillet $^1/_2$ to $^1/_{16}$

c. Common welding process(es) / procedure(s): Weld from center out
Follow class regulations for welding

d. Commonly used filler metal types relative to doubler and hull materials:
7018 rod

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No] Seldom, if at all

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):
Engineering for new build – in field for some smaller ones

16. What design criteria is commonly used:

Try to end next to stiffeners – try to get back

17. Are the doublers approved by a class society: All new builds

a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Check for seal

Sometimes drill hold and pressure or vacuum test, then weld up hole

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): Yes / No

a. If yes, were they intended to be temporary or permanent?

20. Typically how long have you seen doublers last in service: Long as ship life

a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?

OK

FFG – straps to solve cracking problems

a. Are there usually signs of fatigue or fracture? Yes / [✓ No]

i. If so, please describe: Have never seen any signs of stress concentration at edge welds

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No
    a. If so, please describe:
    OK as long as they were sealed

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Dockside - Have diver seal from outside with rubber; then weld doubler inside

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning:
    See no reason not to, if used and installed properly

    For outside shell, much faster and cheaper to use doublers

26. Notes:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 3, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 9
   d. Name of interviewee:
   e. Interviewee’s email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: Repair / New Build / [✓ Both]

3. If New Build, typical applications:

4. If Repair, what types of damage: [✓ Local wastage] / [✓ Pitting] / [✓ Cracks] / Local Buckling

Other / Describe (if possible include probable cause and mode):

For cracks: first try to weld crack, then put doubler over

5. What locations: Any

Long’l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

6. Are repairs with doubler ever intended to be permanent? [✓ Yes] / No If unregulated
7. What is their expected life span: Life of vessel

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):

   Barges, boats, tugs, pushboats

9. Does the service of the vessel affect the decision to use doublers: [✓ Yes] / No

10. If yes, then how:

    a. Cargo Type: Yes
    b. Waterway: Inland / vs offshore
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material:

    A-36

12. Typical doubler plate geometry:

    a. Thickness in relation to parent plate: Thinner than original plate, $^{3}/_{8}$ inch maybe on $^{1}/_{2}$ inch plate – use thinner to minimize heat input and prevent cracking
    b. Min/Max thickness: $^{1}/_{4}$ inch to $^{1}/_{2}$ inch - $^{3}/_{8}$ inch most common, but also $^{1}/_{4}$ inch
    c. Min/Max overall dimensions: 3 inch diameter TO 8 ft by 40 ft sheets
    d. Min/Max aspect ratio: Any
    e. Corner Radii: Yes
    f. End Tapering: No
    g. Other:

13. What surface preparation procedures are commonly performed

(i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):

Blast off paint

14. Weld Details:

    i. Are slot welds used: [✓ Yes] / No

        i. If yes, what is their:

            1. Spacing parallel to stiffeners: Smaller ones no slot welds
            (sometimes big – interviewee saw 8 ft by 6 ft, no slots)
            For big ones, cut out internal existing plate and weld inside
            (circular holes) instead of external plugs
            2. Spacing in second direction:
            3. Common slot W x L: Decisions here owner driven
            4. Sketch (if desired, use back of sheet:

    b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: Standard fillet

    c. Common welding process(es) / procedure(s): Normal

    d. Commonly used filler metal types relative to doubler and hull materials:
    6011 (maybe 7018 cap)

    e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

        If yes, please describe them:

    f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):
Owner specifies desires – yard recommends solution details

16. What design criteria is commonly used:
Owner-driven and experience

17. Are the doublers approved by a class society: No
    a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Air test or vacuum test – some dye penetration

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No
    a. If yes, were they intended to be temporary or permanent?
    Permanent (non-regulated)

20. Typically how long have you seen doublers last in service:
As well as the rest of the vessel
    a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?
Similar to rest of vessel
    a. Are there usually signs of fatigue or fracture? [✓ Yes] / No
        i. If so, please describe: Not in doubler but cracks may continue to grow past doubler

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No
    a. If so, please describe: Don't normally remove

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? In drydock – sometimes dockside

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning:

    Not in fuel tanks, but elsewhere would be OK

26. Notes:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 3, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 10
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

Only uses in pollution emergency or if he knows ship will be in dock in a few months

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Pollution leaks through cracks, hole, or local damage on deck

5. What locations: Any

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	Never put a doubler on a fuel tank boundary or structure Has used doublers on transverse bulkheads of ballast tanks, allowed by ABS until next drydocking				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes [✓ / No] Only temporary

7. What is their expected life span: Short as possible, until current job completed and ship has returned home – cannot wait until next drydocking

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.): Tugs, supply vessels, pushboats

. Does the service of the vessel affect the decision to use doublers: Yes / No

10. If yes, then how:

   a. Cargo Type:
   b. Waterway:
   c. Vessel Route:
   d. Seasonal Restrictions:
   e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material: A-36

12. Typical doubler plate geometry:

   a. Thickness in relation to parent plate: Whatever is available, but at least match the parent
   b. Min/Max thickness: $^5/_{16}$ inch up to $^3/_8$ inch
   c. Min/Max overall dimensions: Min 18 in by 18 in Max 3 ft by 3 ft
   d. Min/Max aspect ratio:
   e. Corner Radii: Yes
   f. End Tapering: Not thick enough
   g. Other:

13. What surface preparation procedures are commonly performed

(i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):
Take paint off

14. Weld Details:

j. Are slot welds used: Yes / [✓ No]

i. If yes, what is their: Normally uses 18” x 18” doublers; no plug welds

1. Spacing parallel to stiffeners:
2. Spacing in second direction:
3. Common slot W x L:
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness:

c. Common welding process(es) / procedure(s): Normal

d. Commonly used filler metal types relative to doubler and hull materials:
7018 – wire feed last pass sometimes

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them:

f. Other prep or post weld details: Sometimes cut ‘X’ in plate before welding edges – weld up afterward – prevent cracking

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):
Interviewee, or shipyard personnel, or ship personnel

16. What design criteria is commonly used:
Experience – tries to get back to flat plate away from damage

17. Are the doubler approved by a class society: Rare, for short term only, if voyage must go now

a. Which one(s): ABS

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Maybe water test or air test, to check if properly sealed

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No

a. If yes, were they intended to be temporary or permanent?

Temporary

20. Typically how long have you seen doublers last in service:

a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?

Seems to be about the same condition as existing structure

a. Are there usually signs of fatigue or fracture? Yes / No

i. If so, please describe:

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No

a. If so, please describe:

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Dockside – have used divers in field

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning: Temporary repair only – no permanent
    None in fuel oil tanks, unless it is no longer used for fuel

26. Notes: Once had a boat take water …

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348,
Design Guidelines for Doubler Plate Repairs of Ship Structures
Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 3, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 11
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: [✓ Repair] / New Build / Both

3. If New Build, typical applications:

Machinery foundations, deck fittings—Used doubler as rub rail on one boat (worked poorly so replaced with half-pipe. Activity is ABS certified; ABS requires inserts minimum of 18 inches by 18 inches

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Wastage, cracks, and holes – temporary repairs only

5. What locations: Any

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL	Never on wet part of boat because can't get at it for maintenance; and once in drydock, use inserts Will use on bulkheads in wet spaces				
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes / [✓ No]
7. What is their expected life span: Short unless minor; then < 2 ½ years

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.): Supply boats and tow boats; this activity specializes in oil rigs

9. Does the service of the vessel affect the decision to use doublers: Yes / [✓ No] Temporary

10. If yes, then how: Only thing is high-load bitts and fittings would require extra strong doubler
    a. Cargo Type:
    b. Waterway:
    c. Vessel Route:
    d. Seasonal Restrictions:
    e. % of time in service:

11. What materials are used for doublers, how do they relate to hull material: A-36

12. Typical doubler plate geometry:
    a. Thickness in relation to parent plate: About $^{1}/_{2}$ in, sometimes $^{3}/_{4}$ inch or 1 inch
    b. Min/Max thickness: Minimum $^{3}/_{8}$ inch
    c. Min/Max overall dimensions: Whatever is necessary – no set minimum
       Some length of vessel, but typical 2 ft by 2 ft max
    d. Min/Max aspect ratio: As needed
    e. Corner Radii: Yes - 3 to 4 inches
    f. End Tapering: Yes
    g. Other:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):

Knock paint off

Where welding – prime doubler, blast and zinc plate before installing

14. Weld Details:

k. Are slot welds used: [✓ Yes] / No

i. If yes, what is their:

1. Spacing parallel to stiffeners: On stiffeners 8” to 12” min
2. Spacing in second direction: 12 inches??
3. Common slot W x L: 1-2 t x 2 inches, fill solid
4. Sketch (if desired, use back of sheet:

b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness: By eye until it looks right, but ABS usually accepts

c. Common welding process(es) / procedure(s): Normal

d. Commonly used filler metal types relative to doubler and hull materials:

6011 first pass and 7018 on cap passes

e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

If yes, please describe them:

f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.):

Ship operator rep if at home port – welder if ship operator rep is elsewhere

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

16. What design criteria is commonly used:

Nothing is codified – goes by experience

Try to attach to existing structure

17. Are the doublers approved by a class society: No

a. Which one(s):

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Visual only

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): Yes / No

a. If yes, were they intended to be temporary or permanent?

Can't remember for boats bought in mid-service life

20. Typically how long have you seen doublers last in service:

a. What is the oldest seen?

21. What is the condition of a typical doubler after its service life?

a. Are there usually signs of fatigue or fracture? Yes / [✓ No]

i. If so, please describe: None that interviewee remembers

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? Yes / No

a. If so, please describe:

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Dockside or in field

24. Have any unusual geometry or welding schemes been encountered: Yes / No
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning:
    Great for temporary repairs, but careful not to end up with boat having doublers all over

26. Notes:

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

Ship Structure Committee Project, SR-1348, Design Guidelines for Doubler Plate Repairs of Ship Structures Shipyard/Ship Owner Questionnaire

1. General Info:
   a. Date: June 4, 2004
   b. Name of interviewer: Dan Gallagher and Malcolm Willis
   c. Name of shipyard/ship owner: Company 12
   d. Name of interviewee:
   e. Interviewee's email address and phone no

SECTION I – EXPERIENCE INSTALLING DOUBLERS

2 How does the yard use doublers/straps: Repair / New Build / [✓ Both]

3. If New Build, typical applications:

Under machinery, etc.

4. If Repair, what types of damage: Local wastage / Pitting / Cracks / Local Buckling

Other / Describe (if possible include probable cause and mode):

Holes, wastage, pitting

5. What locations:

Long'l Position/ Structure Type	Aft Peak	0.75 L	Midship	0.25 L	Fore Peak
Side Pl Abv WL					
Side Pl Blw WL					
Bottom Pl					
Major Bhd Pl					
Minor Bhd Pl					
Shell Stiff web/fl					
Other Stiff web/fl					

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

6. Are repairs with doubler ever intended to be permanent? Yes / No
7. What is their expected life span: ______

8. On what types of vessels has the yard applied doublers (i.e. ferries, cargo ships, etc.):
   Barges, tugs, supply boats, fishing vessels

9. Does the service of the vessel affect the decision to use doublers: Yes / No

10. If yes, then how:
    - a. Cargo Type: ______
    - b. Waterway: ______
    - c. Vessel Route: ______
    - d. Seasonal Restrictions: ______
    - e. % of time in service: ______

11. What materials are used for doublers, how do they relate to hull material:
    A-36 AL – 5000 series

12. Typical doubler plate geometry:
    - a. Thickness in relation to parent plate: $^3/_8$ inch most common, at least as much as parent plate
    - b. Min/Max thickness: Minimum $^3/_8$ inch to $^1/_2$ inch
    - c. Min/Max overall dimensions: 6 inch diameter to full plate 10 ft by 40 ft
    - d. Min/Max aspect ratio: ______
    - e. Corner Radii: Yes, minimum 3 inches
    - f. End Tapering: For thick plates
    - g. Other: ______

13. What surface preparation procedures are commonly performed (i.e. remove existing paint and corroded material, fair plating to ensure it is flat, etc):
    Knock paint off

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Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

14. Weld Details:

    l. Are slot welds used: [✓ Yes] / No

        i. If yes, what is their:

            1. Spacing parallel to stiffeners: ~ 12” to 18” No indication of matching stiffener (even though interviewer asked)
            2. Spacing in second direction: ~ 12” to 18”
            3. Common slot W x L: 1 in x 3 in (fillet only)
            4. Sketch (if desired, use back of sheet:

    b. Size of welds (inches or mm) relative to the doubler plate thickness and hull plate thickness:

    c. Common welding process(es) / procedure(s): Mig (wire feed)

    d. Commonly used filler metal types relative to doubler and hull materials: 0.0035 wire

    e. Are Pre- or post weld heat treatments commonly used? Yes / [✓ No]

        If yes, please describe them:

    f. Other prep or post weld details:

15. Who typically designs doubler plates (i.e. shipyard, engineering firm, etc.): Project Manager

16. What design criteria is commonly used: Experience, rules of thumb

Try to catch adjacent structure

17. Are the doublers approved by a class society: Not by this interviewee, but some do
    a. Which one(s): ______

18. What quality assurance procedures are commonly performed (i.e. check welds by radiographic or ultrasonic techniques)?

Air test or vacuum box – check seal integrity

______

SECTION II – EXPERIENCE WITH PREVIOUSLY ISNTALLED DOUBLERS

19. Do you see doubler repairs previously installed (by this yard or others): [✓ Yes] / No
    a. If yes, were they intended to be temporary or permanent?
       Permanent

20. Typically how long have you seen doublers last in service: ______

______

    a. What is the oldest seen? ______

21. What is the condition of a typical doubler after its service life?
    Seems to be no worse than original plate

______

    a. Are there usually signs of fatigue or fracture? Yes / [✓ No]
       i. If so, please describe: ______

______

______

22. When doublers have been removed have you seen signs of damage that would have been hidden otherwise? [✓ Yes] / No
    a. If so, please describe: ______

Ship Structure Committee Project, SSC 03-12,

Design Guidelines for Doubler Plate Repairs of Ship Structures

Shipyard/Ship Owner Questionnaire

23. What facilities (yard, dockside service, divers etc.) have been used to install the temporary doublers? Dockside or on rails

24. Have any unusual geometry or welding schemes been encountered: Yes / [✓ No]
    a. If so, please describe:

SECTION III – CONCLUSION & NOTES

25. Would you recommend the use of doubler plate repairs: [✓ Yes] / No
    a. Please expand on reasoning:

If they allow ‘temporary’ repair for one or two years, why not more?

Can be good for extended use, as long as you can tie back to good plate

26. Notes:

Saw doubler on aluminum ferry that was riveted on – turned out to be over a crack

Seemed to work, crack had not traveled (back on transom near jet drives, high vibration)

Saw barge with big doublers on internal longitudinal bulkhead – full sheets of steel

8 ft by 40 ft with plug welds – took off and replaced but it seemed to be working

Had been there 3 to 5 years

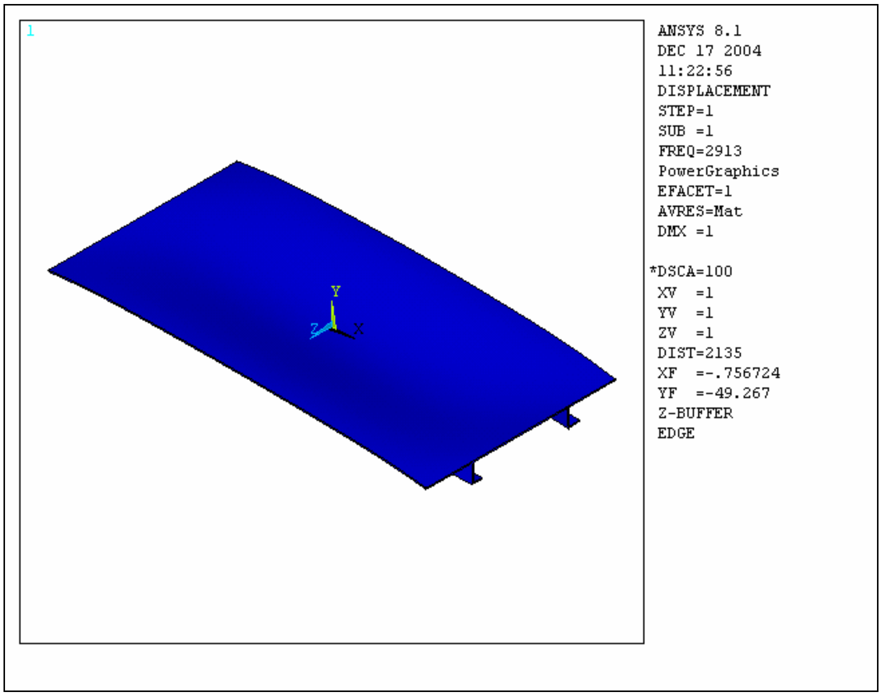
Saw an old OSV (being converted) with bottoms of longitudinal bulkheads that had been

doubled (18 in high). Worked until then.

Interviewee has never seen a doubler fail

APPENDIX C: DEFLECTION AND STRESS PLOTS

C1 Buckling Plots- Section 5 (Displacement Scaling Factor of 100)



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DEC 17 2004
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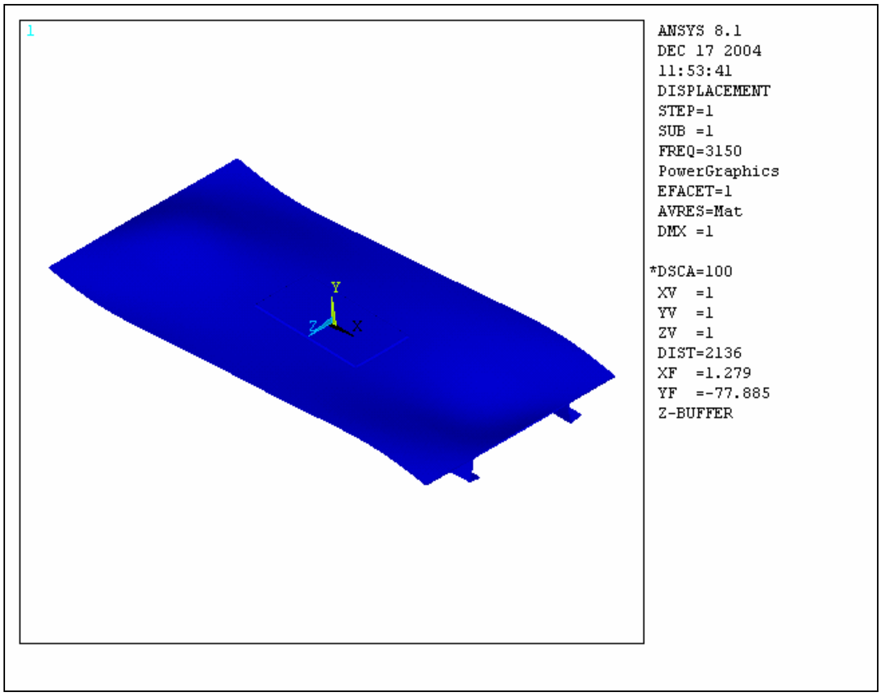
PowerGraphics
EFACET=1
AVRES=Mat
DMX =1

*DSCA=100
XV  =1
YV  =1
ZV  =1
DIST=2135
XF  =-.756724
YF  =-49.267
Z-BUFFER
EDGE
```

Figure C.1: Base Case- Mode 1



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11:53:41
DISPLACEMENT
STEP=1
SUB =1
FREQ=3150
PowerGraphics
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AVRES=Mat
DMX =1

*DSCA=100
XV  =1
YV  =1
ZV  =1
DIST=2136
XF  =1.279
YF  =-77.885
Z-BUFFER
```
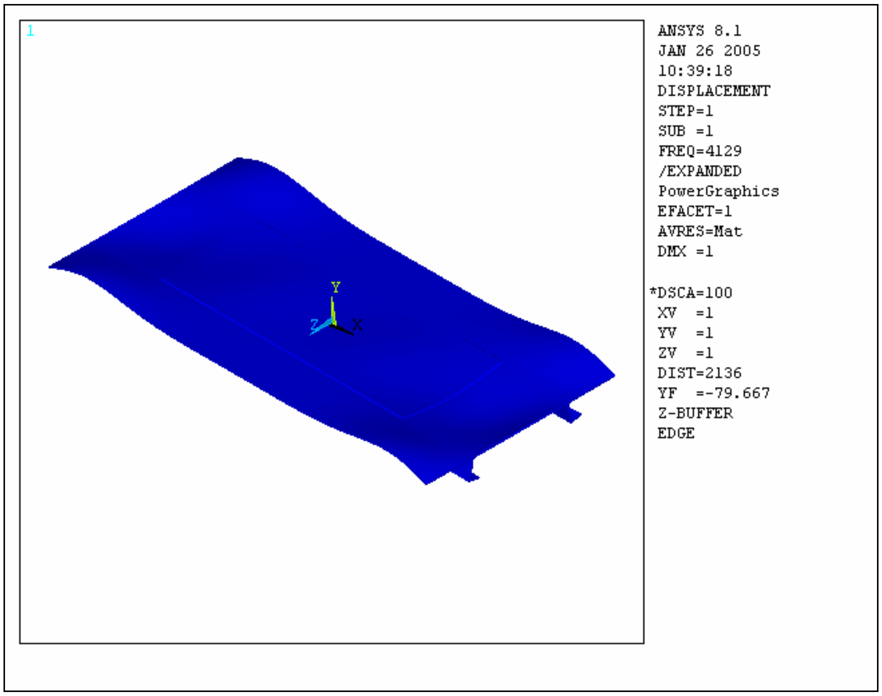

Figure C.2: Case 25- Mode 1



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JAN 26 2005
10:39:18
DISPLACEMENT
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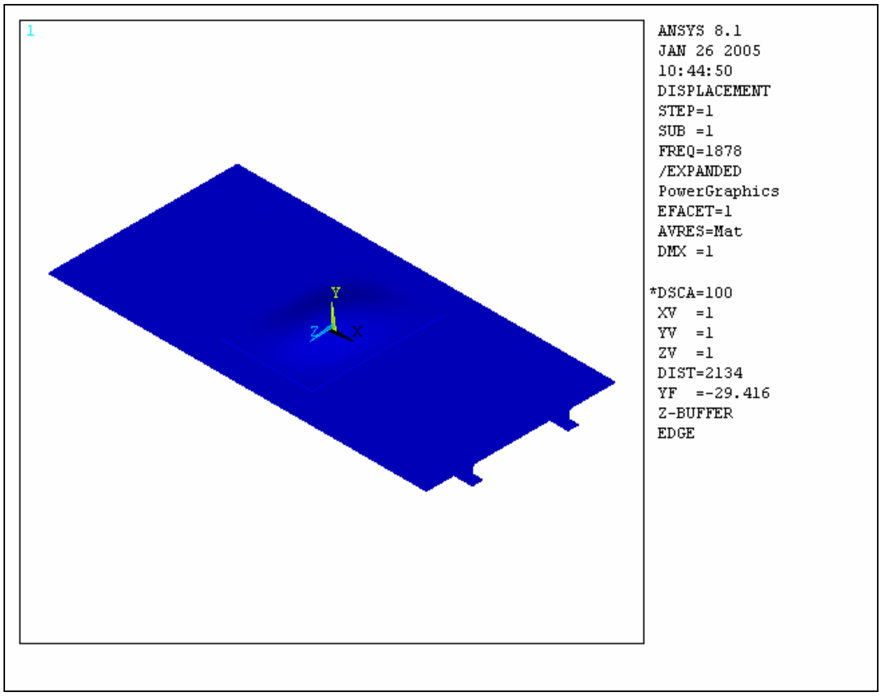
SUB =1
FREQ=4129
/EXPANDED
PowerGraphics
EFACET=1
AVRES=Mat
DMX =1

*DSCA=100
 XV  =1
 YV  =1
 ZV  =1
 DIST=2136
 YF  =-79.667
 Z-BUFFER
 EDGE
```

Figure C.3: Case 32- Mode 1



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JAN 26 2005
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FREQ=1878
/EXPANDED
PowerGraphics
EFACET=1
AVRES=Mat
DMX =1

*DSCA=100
 XV  =1
 YV  =1
 ZV  =1
 DIST=2134
 YF  =-29.416
 Z-BUFFER
 EDGE
```

Figure C.4: Case 36 – Mode 1

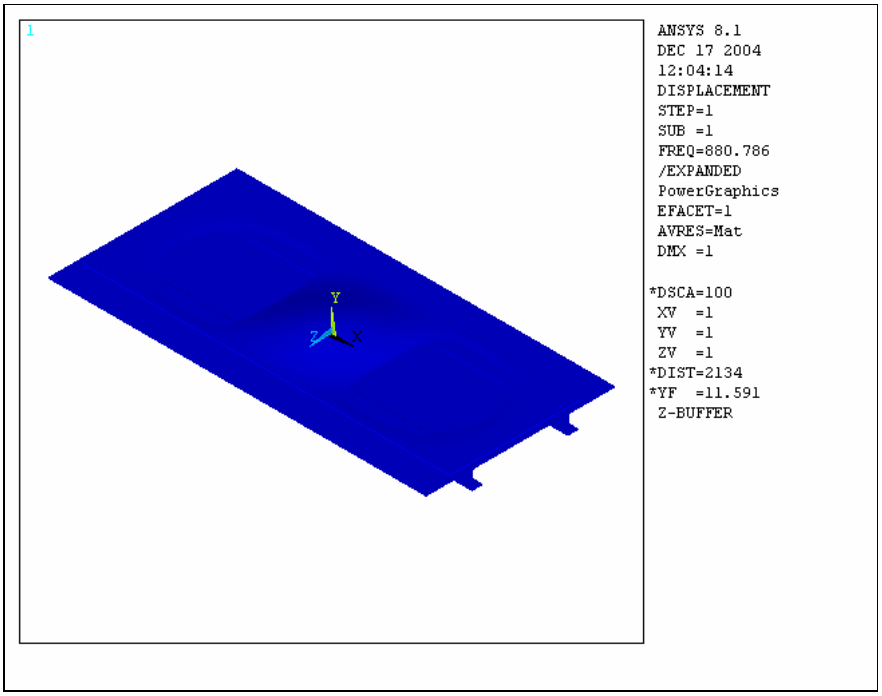


Figure C.5: Case 48 a – Mode 1

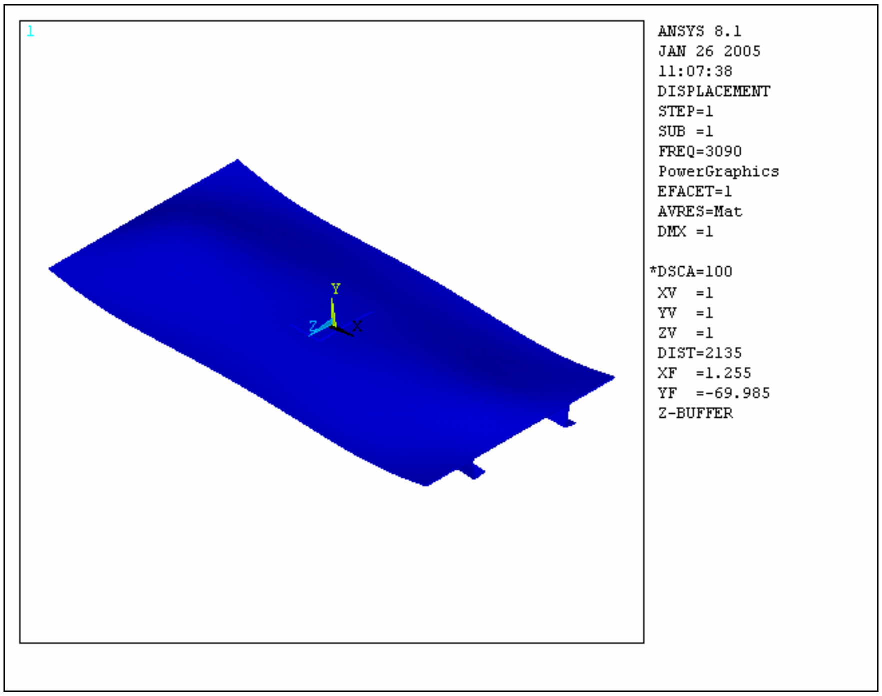
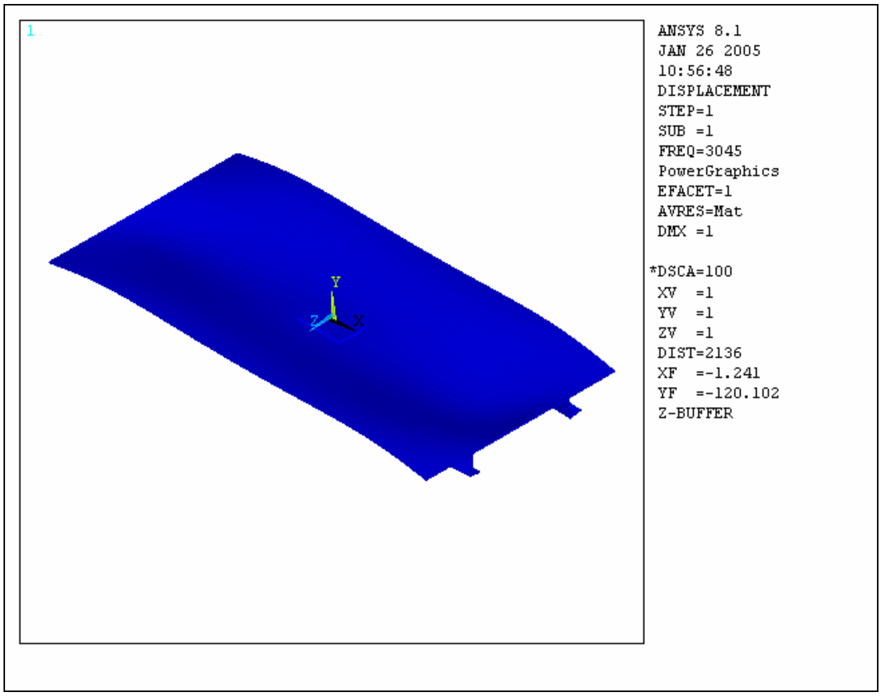


Figure C.6: Case 17 – Mode 1



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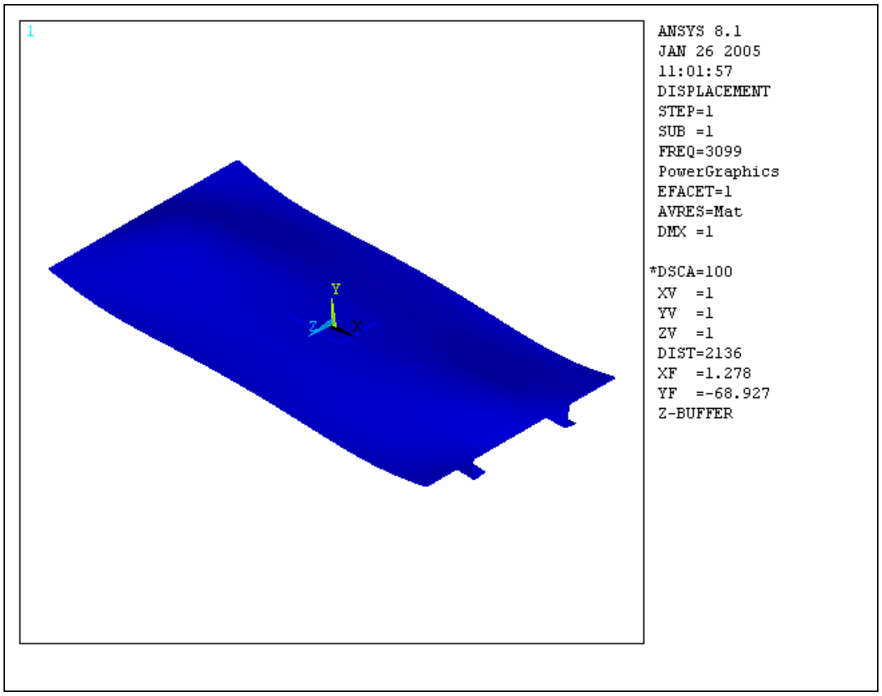
AVRES=Mat
DMX =1

*DSCA=100
XV =1
YV =1
ZV =1
DIST=2136
XF =-1.241
YF =-120.102
Z-BUFFER

Figure C.7: Case 10 – Mode 1



ANSYS 8.1
JAN 26 2005
11:01:57
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FREQ=3099
PowerGraphics
EFACET=1
AVRES=Mat
DMX =1

*DSCA=100
XV =1
YV =1
ZV =1
DIST=2136
XF =1.278
YF =-68.927
Z-BUFFER

Figure C.8: Case 11 – Mode 1

C2 - Section 6.1: Effect of Corner Radius- Von-Mises Stress (MPa) Plots

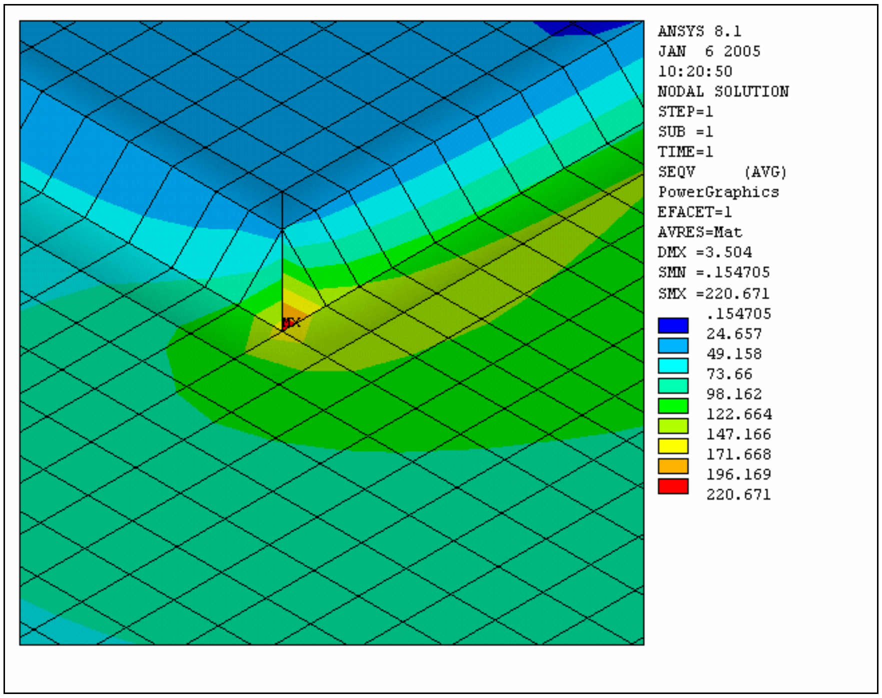

Figure C.9: Base Case A – Doubler with no radius

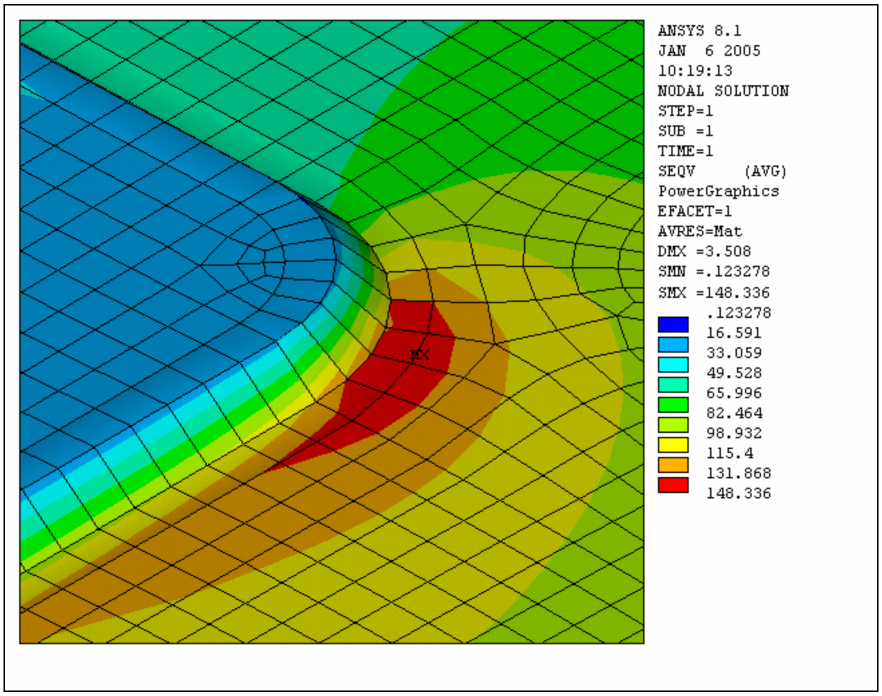

Figure C.10: Case 1A – Doubler with corner radius = 50.8 mm

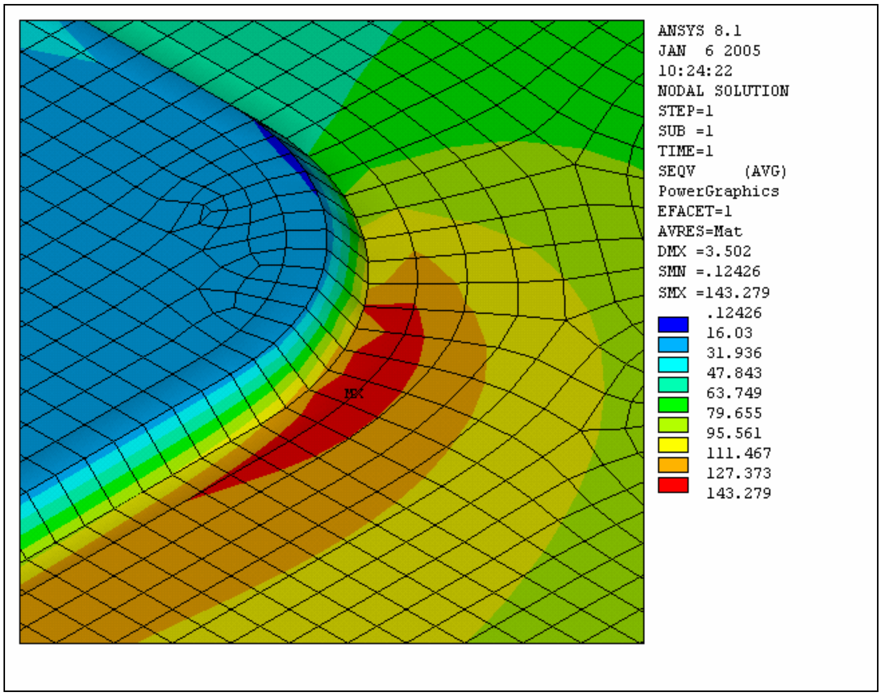

Figure C.11: Case 2A – Doubler with corner radius = 101.6 mm

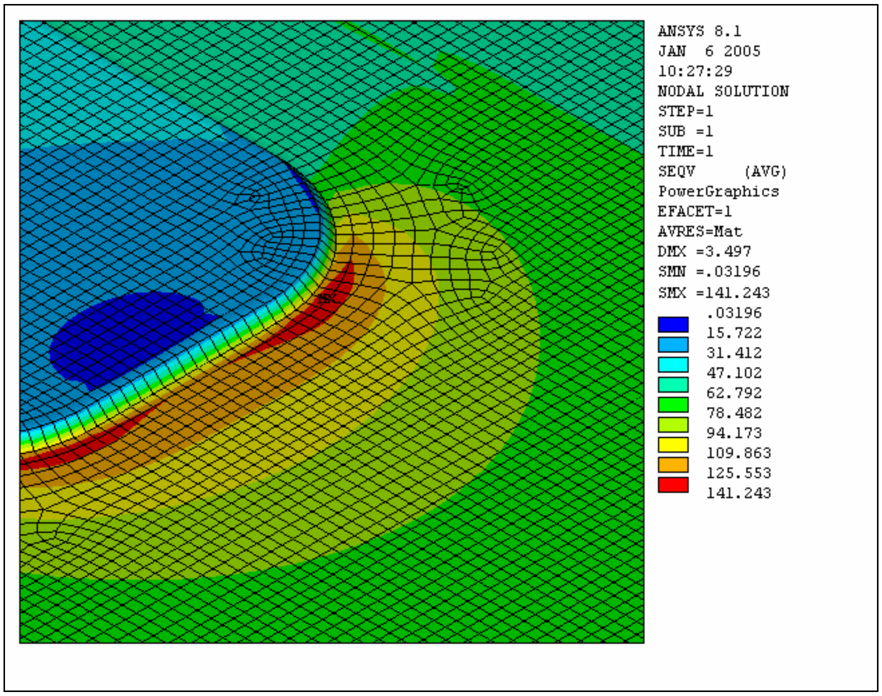

Figure C.12: Case 2A – Doubler with corner radius = 152.4 mm

C3 - Section 6.2: Von-Mises Stress (MPa) Plots

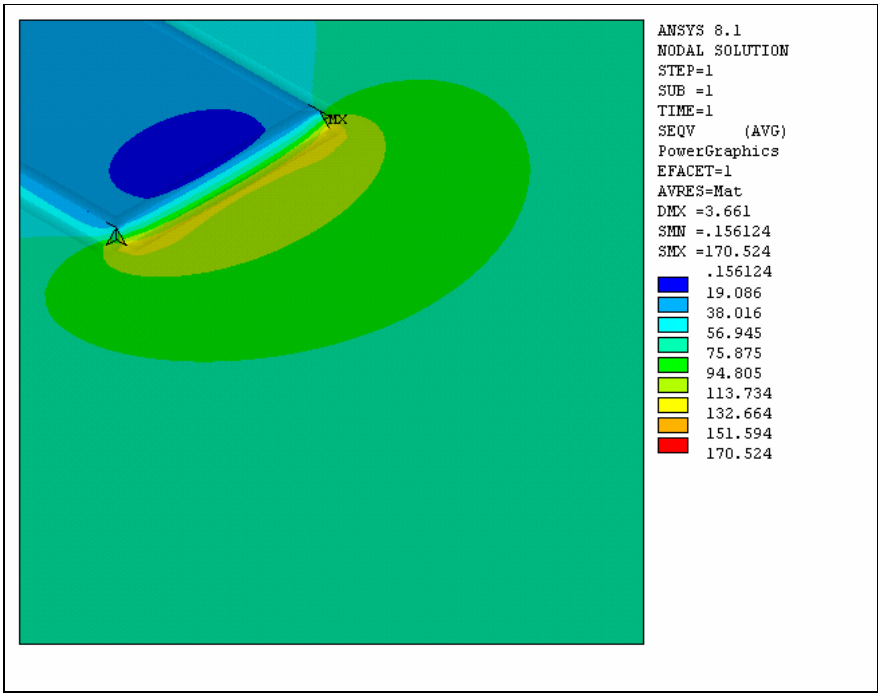

Figure C.13: Case 14-Tension loading

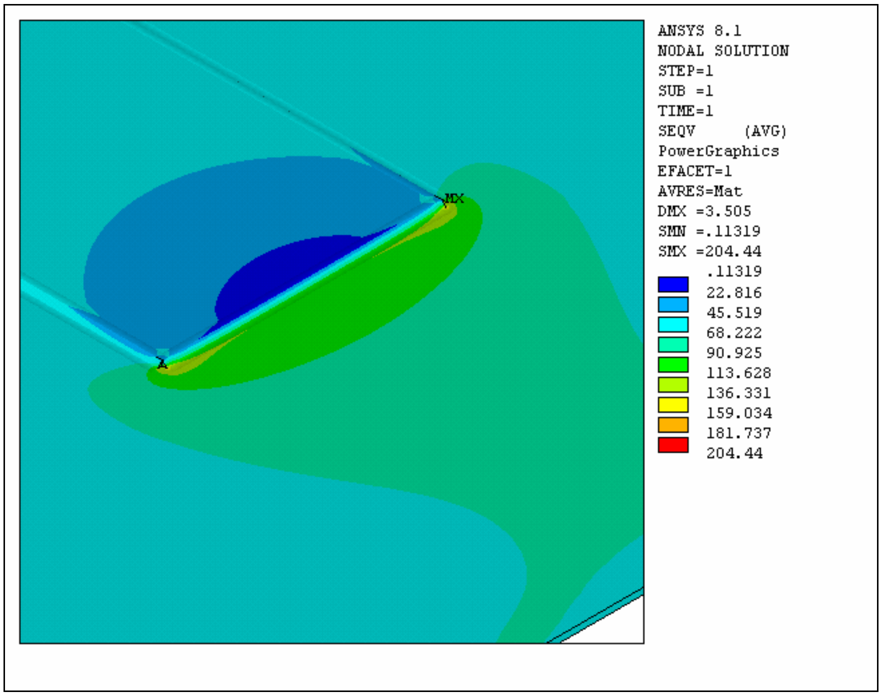

Figure C.14: Case 30- Tension loading

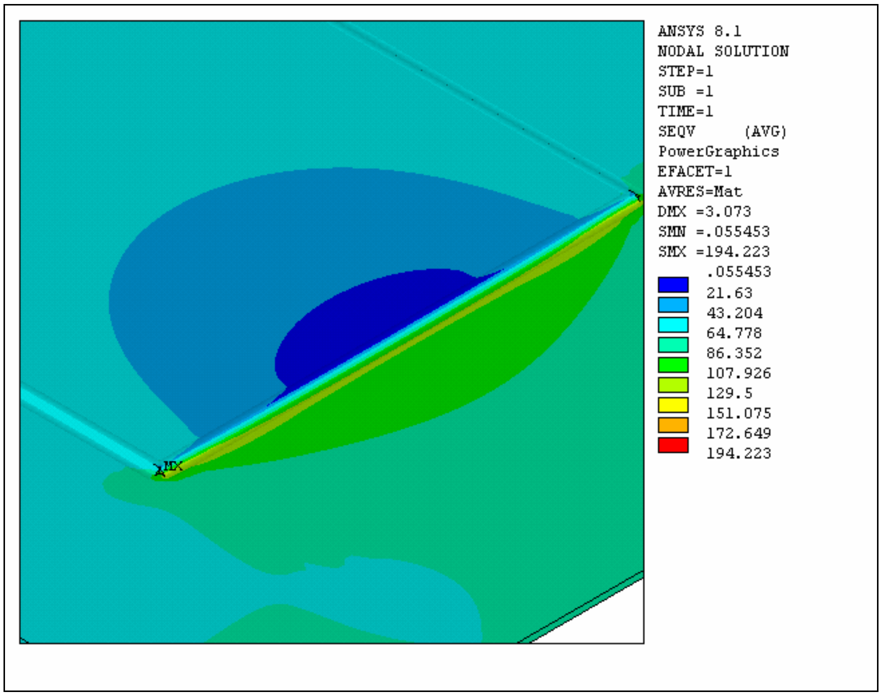

Figure C.15: Case 32- Tension loading

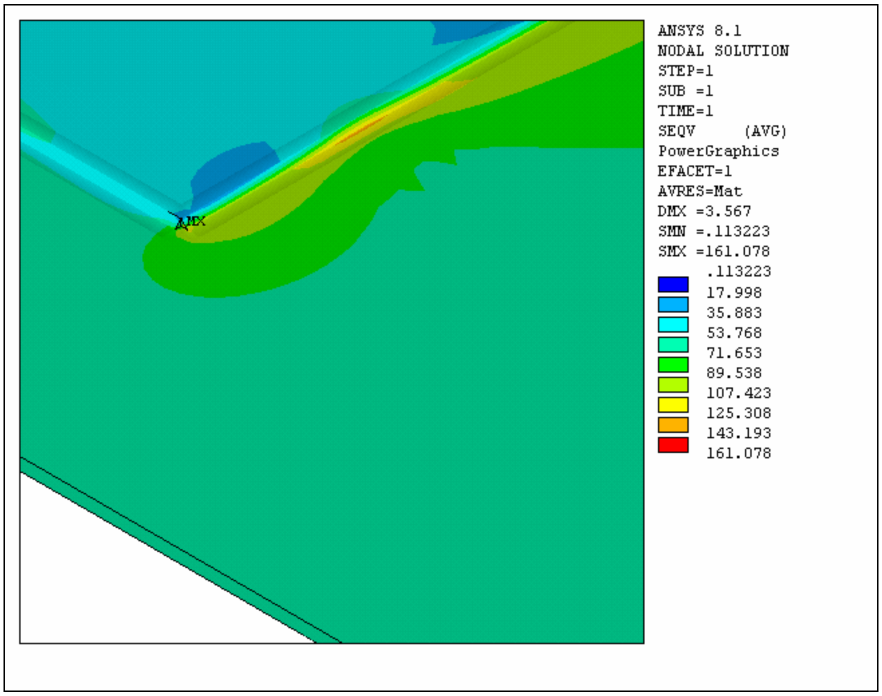

Figure C.16: Case 36- Tension loading

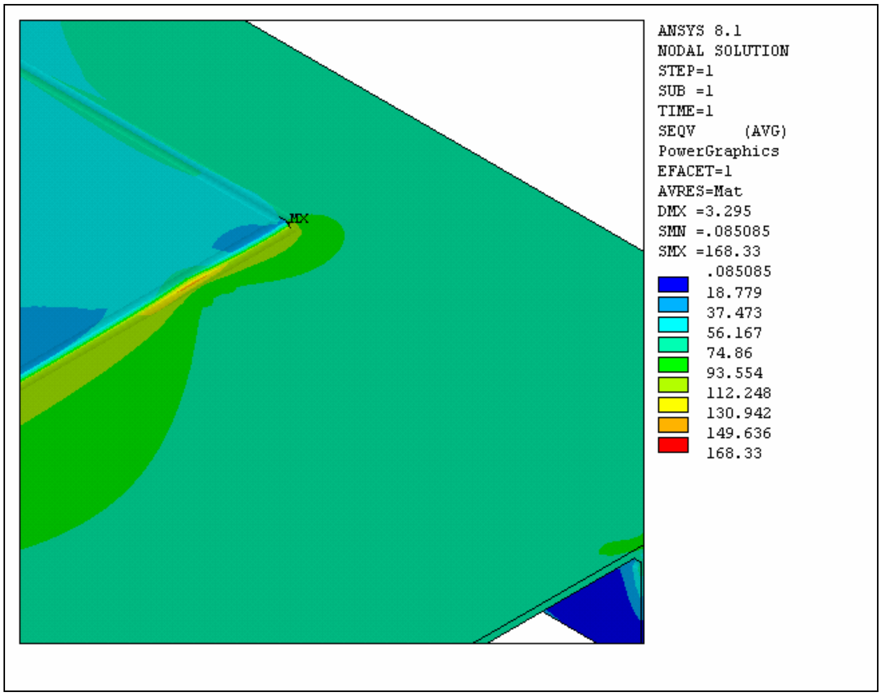

Figure C.17: Case 44- Tension loading

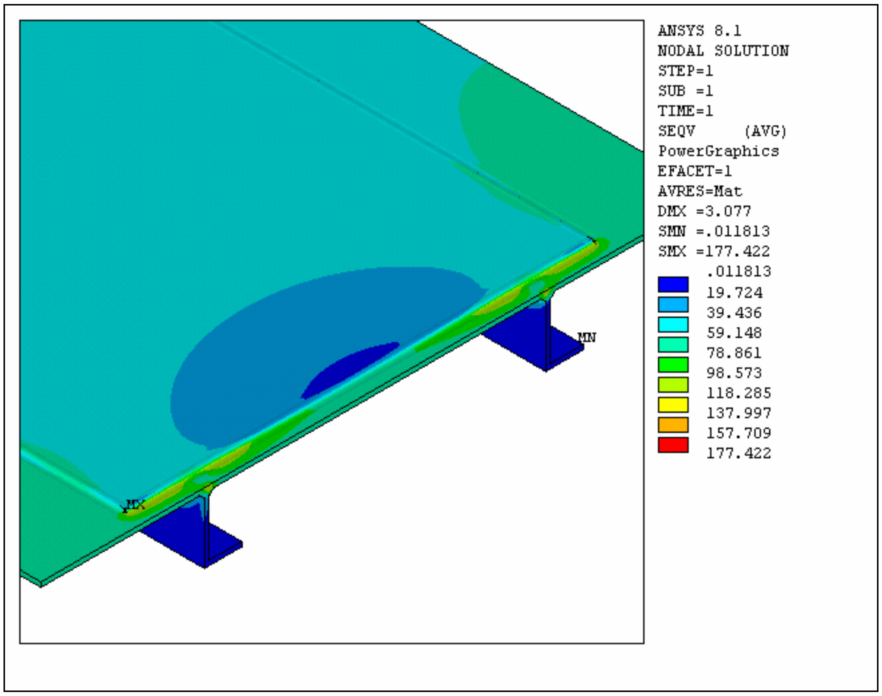

Figure C.18: Case 48- Tension loading

C4 - Section 6.3: Von-Mises Stress (MPa) Plots

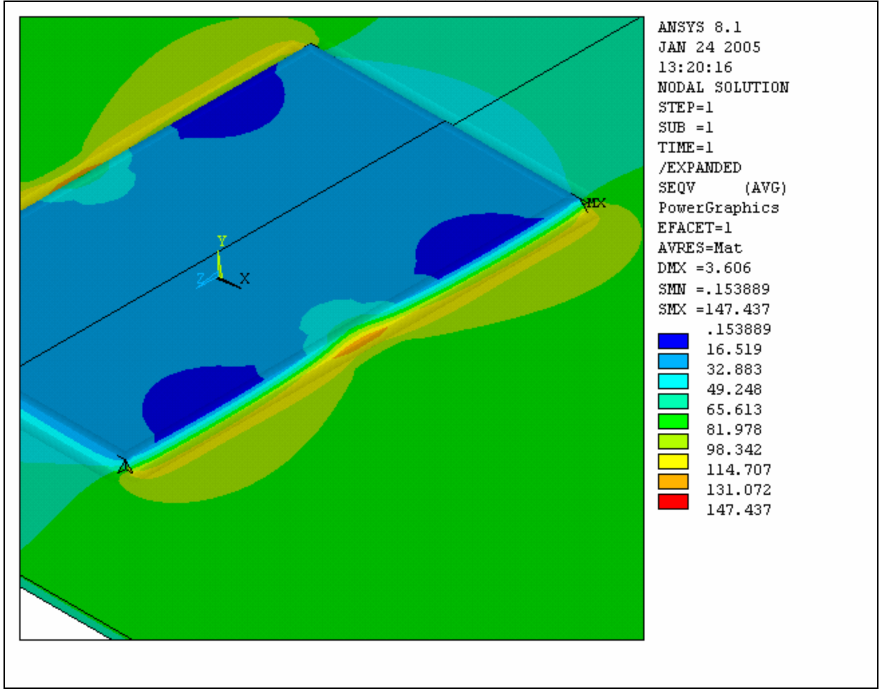

Figure C.19: Case 4- Tension Loading

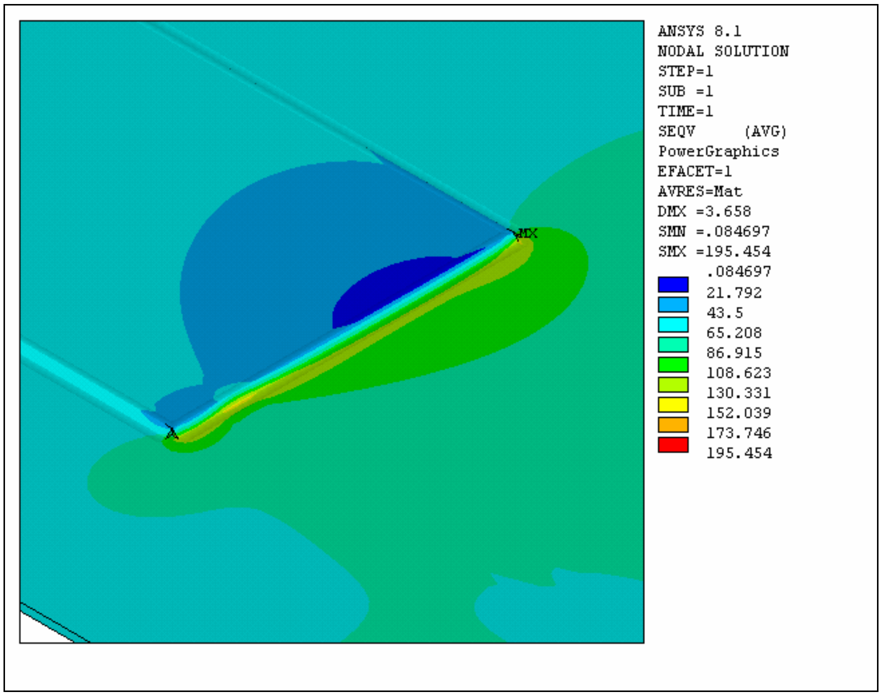

Figure C.20: Case 15- Tension Loading

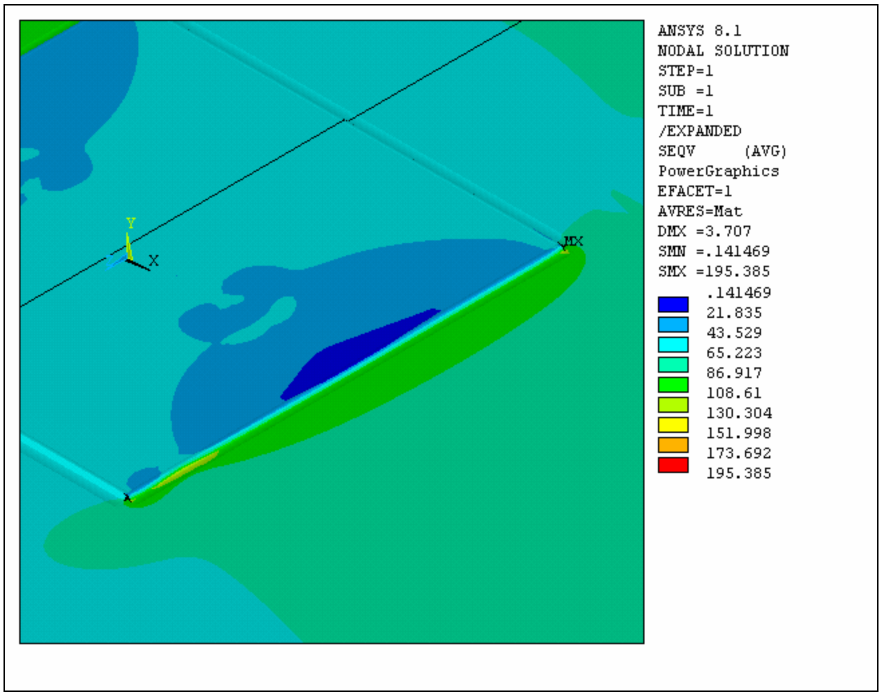

Figure C.21: Case 35- Tension Loading

PROJECT TECHNICAL COMMITTEE MEMBERS

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, performed technical review of the work in progress and edited the final report.

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Members **Contracting Officer's Technical Representative:**		
	Ms. Theresa Garnes	NAVSEA
Project Technical Committee Members:		
Executive Director:		
	LT Eric M. Cooper	USCG
Administrative Assistant:		
	Ms. Jeannette Delaney	ARTI, USCG

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SSC Report Number	Report Bibliography
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SSC 440	Deterioration of Structural Integrity Due to Chemical Treatment of Ballast Water S. Tiku, 2005
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