9 Conclusions

9.1 SUMMARY

A series of six experiments were conducted to define crack behavior in stiffened panels. These tests provided valuable information regarding the effects of both stiffener geometry and residual stress on crack growth rates. Variability of crack tip growth rates was seen within each test. This variability was attributed primarily to differences in the residual stress distribution. To assess the residual stresses, measurements were made in two of the specimens. Also, complete records of stress levels were recorded as the crack grew in the panel. These stress readings were used to develop guidelines on choosing a representative uniform stress for use in crack growth prediction.

Analytical modeling was performed to predict the experiments. A simple model for the residual stress distribution was included. The analytical model demonstrated that simple fracture mechanics principles could be used to effectively determine crack growth rates. Superposition was used in the analytical model to combine the effects of residual stresses, stiffener separation, and stiffener restraint on crack growth rates. The effect of the finite width correction was also reviewed throughout the modeling. Parametric investigations with the model resulted in guidelines for proper life prediction based on consistent rational assumptions.

A finite element modeling technique was developed as well, including an evaluation into the use of gap elements. The gap elements prevented overlapping of crack faces but also introduced nonlinearity in the formulation. A finite element model that excluded the gap elements was developed in which superposition was valid. This finite element model gave virtually identical results as the analytical model. By including gap elements, however, small differences were seen between analytical model and the F.E. model. A method was

developed to obtain the results obtained with gap elements from a FE model without gap elements. The differences between models with and without gap elements diminish when the applied load overcomes the effects of crack closure. Finite element modeling is more time consuming but may be necessary for cracks in complicated geometries.

All of the prediction methods were sensitive to the specified residual stress distribution for low applied stresses. Various assumptions about the distribution of the applied and residual stresses can affect the results profoundly. However, when results are obtained from a rational and consistent set of assumptions, both the finite-element and the analytical models can simulate measured crack growth conservatively and reasonably accurately. The inherent variability of residual stress does not allow for very accurate predictions, however. Therefore, the approach taken is to develop conservative models based on worst-case residual stress distributions.

Since a typical default conservative assumption in these type of calculations is that there is little or no crack closure, this is the same as assuming that the worst case large tensile residual stresses are present. Therefore, the effects of residual stress only decrease crack growth rates. This is because the applied stress range is used in the Paris Law, and compressive residual stress may make the applied stress range less effective by contributing to crack closure.

9.2 FINDINGS

The findings of this research may be divided into sections:

I. Experimental observations

   A. The effect of redundancy was observed in these test structures. The test specimens shed load as they cracked which allowed the cracks to grow in a stable manner to a total length exceeding one meter.

B. Solid stiffeners will slightly slow down an approaching crack. Stiffeners with cutouts (ratholes or raised drain holes), however, provide no restraint on crack opening and consequently no retardation can be expected. If there as a butt weld in the plate nearby and parallel to the crack, accelerated growth similar to an unstiffened, cracked plate may be expected.

C. Residual stress distributions have substantial variability. At low stresses typical for fatigue crack growth, this variability will significantly influence the accuracy of predictions. In the stiffened panel tests, compressive residual stress between stiffener spacings significantly retarded crack growth rates. In fact, there was significant difficulty starting a crack centered between stiffeners. The effect of residual stresses far outweighs the effect of other variables.

D. Shear lag effects led to non-uniform applied stress distributions in the specimens. These shear lag effects also occur in ship structure, however. Continuous stress monitoring was used to record the history of stress changes.

E. After the cracks encountered the solid stiffeners, the rate of propagation up the web of the stiffener was similar to the rate of propagation in the plate beyond the stiffener. Even in the stiffeners with ratholes or raised drain holes in the propagation path, cracks started at the apex of the holes as soon as the plate crack had reached a distance from the stiffener equivalent to that of the cutout height above the plate. This equivalent growth rate persisted until the stiffener crack encountered the flange of the stiffener.

II. Analytical Model Observations

A. The analytical model correlated well with finite element modeling.

B. An attempt to correct for the increase in stress due to a reduction in the net section overestimated crack growth rates. The correction becomes more applicable with decreasing redundancy in a structure. In other situations, such as the test setup, load was redistributed in a manner not proportional to the flexure formula.

C. Stress gradients across the width of the panel are easily incorporated into the analytical model by adjusting the stiffener areas.

D. For butt welded plates and multiple propagating cracks, an analytical prediction based on the stress-intensity factor for a flat plate is sufficient.

III. Finite Element Modeling Observations

A. Using gap elements reduces the available effective range in stress-intensity factor (ΔK_{eff}) in some situations. This occurs because crack closure effects behind the crack tip promote residual stress redistribution. Excluding gap elements allows superposition to be used in determining K_{total}. The results without gap elements compare well with the analytical model. Finite element modeling generally predicts less conservative results by including gap elements with an initial gap of zero meters.

B. Any effects of gap elements are negligible when external load completely opens the crack.

C. Applying temperature loads to nodes within the weld regions can reproduce residual stress distributions.

D. Finite element modeling can be quite time consuming compared to the analytical model. Furthermore, no greater accuracy is seen in the typical studies conducted in this report. It is recommended to use finite element modeling to determining a local uniform stress in the structure (without a crack) and then use this stress in the analytical model to include the effect of the crack.

IV. Miscellaneous Observations

A. The support structure was subjected to repeated instance of fatigue cracking. These cracks were repaired by a variety of methods. As testing continued, some repairs performed better than others. A complete report of the cracking, repair method, and repair performance at a number of locations is included in Appendix A.

B. Redundant structures exhibit a great amount of symmetry. For instance, cracking in an area of one support beam promoted cracking in its parallel counterpart. This was due to load shedding.

C. Fatigue cracks may often be repaired by simply drilling out the crack tip and welding the crack faces together. The repair is discussed in detail in Appendix

A. This repair significantly increases fatigue life with little effort since the majority of fatigue life is seen when the crack is relatively short. The downside to this quick repair is that any future crack growth will occur at a slightly increased rate.

D. Other performance-based repairs make treating these fatigue crack problems in older ship structure more economical. These types of repairs are suggested for review in the next section.

9.3 MAIN CONCLUSIONS

1. The behavior of cracks in redundant welded stiffened panels is substantially different than predicted using conventional fracture mechanics solutions for a crack in a plate.
2. Redundancy of the structure and reasonable fracture toughness of the steel allowed the stable growth of cracks more than a meter in total length. The compliance of the cracked elements cause them to shed load to adjacent elements in the structure.
3. Compressive residual stresses between stiffeners significantly retards the rate of crack growth. However, if there as a butt weld in the plate nearby and parallel to the crack, accelerated growth similar to an unstiffened, cracked plate occurs.
4. An analytical model was developed that can simulate these effects of welded stiffeners and provide reasonably accurate worst-case predictions of the propagation of very long cracks in welded stiffened panels.
5. Residual stress distributions have substantial variability. At low stresses typical for fatigue crack growth, this variability will significantly influence the accuracy of predictions. The effect of residual stresses far outweighs the effect of other variables.
6. Finite-element modelling of the cracked stiffened panels verified the analytical model but offered no greater accuracy for the cases studied. It is recommended to use finite element modeling to determining the stress distribution in the structure (without a crack) and then use this stress in the analytical model to include the effect of the crack.

9.4 RECOMMENDATIONS FOR FUTURE WORK

The analytical model described in this report should yield a reasonably adequate prediction, especially considering the high variability seen under even constant amplitude loading.

The experiments suggest further review of several parameters, however. First, the stiffener sizes remained constant throughout the testing. The crack propagation in panels with different stiffener areas is likely to be similar and therefore reasonably well predicted by the model. However, confirmation of the behavior with different stiffener areas would facilitate wider acceptance of the model.

The added effects of pressure loading should also be investigated. Watanabe and Kawano [166] performed a limited study of this situation and predicted crack growth through finite element analysis. The effect of pressure on the shell may be significant.

Residual stress is inherently highly variable. Further investigation into quantifying residual stress will not improve the situation unless assembly order is known a priori and carefully controlled during fabrication.

Predicting fatigue cracks allowed for speculation on the best and easiest repairs to make in cracking situations. Stiffeners that are not welded to the plate will significantly decrease crack growth rates. For this reason, it would be worth examining the feasibility of using adhesive-bonded plates to arrest crack propagation.

An immediately applicable repair involves a more conventional welding approach. Holes are drilled at the crack tips and the crack faces are welded up to the drilled holes (See Figure 11-6 and Figure 11-9). Additional reinforcement can be added by welding plate strips

across the crack. This repair detail will not perform as well as the original continuous base metal, but the repair can be quickly implemented resulting in considerable additional life. For example, a section in the support structure repeatedly cracked and was repaired with a complete penetration plug weld. Each repair afforded continued use of the section for one million cycles at a measured stress range of 80 MPa. This type of performance-based repair could serve the aging tankships in the TAPS trade until they are slated for retirement.

If watertightness is not a concern, drilling a stop hole alone may be used to arrest the crack without the weld repair. The key to drilling a stop hole is the size of the hole, as described in Equation 11-1.

Fatigue involves a great amount of variability. When combined with an equally variable loading environment, the possibility of developing a model that correctly addresses all parameters is impossible. Reasonable models, such as the ones presented in this report, should be coupled with a reasonable models to predict the loading.

10 REFERENCES

1) Aihara, S., et al. (1995, December) Fracture Mechanical Modeling of Brittle Crack Propagation and Arrest in Steel. J. Soc. of Naval Arch. of Japan, Vol. 178, pp. 545-555.

2) Alman, P., W.A. Cleary, Jr., M.G. Dyer, and J.R. Pauling. (1992) The International Load-Line Convention: Crossroads to the Future. Marine Technology, Vol 29, N 4, pp. 233-249.

3) Almer, J.D., K.R. McCallum, and R.A. Winholtz. X-Ray Diffraction and Finite Element Study of Residual Stress Effects on Fatigue Crack Growth. Technical Report #34. Office of Naval Research, May 1997.

4) Alpsten, GA, and L. Tall. (1970) Residual Stresses in Heavy Welded Shapes. Welding Journal, Vol. 49, Research Supplement. pp. 93-s to 105-s.

5) American Bureau of Shipbuilding, Guide for Fatigue Assessment of Tankers. New York, NY: ABS, 1992.

6) Anderson, T.L. Fracture Mechanics - Fundamentals and Applications. (2nd ed.) Boca Raton, Florida: CRC Press, 1995.

7) Argyris, J.H., J. Szimmat, and K.J. William. (1982) Computational Aspects of Welding Stress Analysis. Computer Methods in Applied Mechanics and Engineering, Vol. 33, pp. 635-666.

8) Arin, K. (1979) Several Intact or Broken Stringers Attached to an Orthotropic Sheet with a Crack. Engineering Fracture Mechanics, Vol 3, pp. 1-8.

9) ASTM. Methods and Models for Predicting Fatigue Crack Growth Under Random Loading. ASTM Special Technical Publication 748. Ed. J.B. Chang and C.M. Hudson. Philadelphia, PA: American Society for Testing and Materials, 1981.

10) ASTM. Probabilistic Fracture Mechanics and Fatigue Methods: Applications for Structural Design and Maintenance. ASTM Special Technical Publication 798. Ed. J.M. Bloom and J.C. Ekvall. Philadelphia, PA: American Society for testing and Materials, 1981.

11) Averbach, B.L. and Bingzhe Lou. (1984) Fatigue Crack Propagation through Residual Stress Fields. Metal Trans. A (USA), pp. 1631-1640.

12) Bacci, A. and S. Ligaro. (1996) Competition Between Brittle fracture and Plastic Collapse in the Failure of Thin Rectangular Panels. Intl. J. of Fracture, Vol 77, pp. 185-198.

13) Barsoum, R.S.. (1976) On the Use of Isoparametric Finite Elements in Linear Fracture Mechanics, International Journal for Numerical Methods in Engineering, Vol. 10, pp. 25-37.

14) Barsom, J.M. Fatigue Crack Growth Under Spectrum Loads. ASTM Special Technical Publication 595. Philadelphia, PA: American Society for Testing and Materials, 1976. pp. 217-235.

15) Barsom, J.M. and S.T. Rolfe. (1987). Fracture and Fatigue Control in Structures. 2nd ed. Englewood Cliffs, New Jersey: Prentice-Hall.

16) Beghini, M., L. Bertini and E. Vitale. (1994) Fatigue Crack Growth in Residual Stress Fields: Experimental Results and Modeling. Fatigue and Fracture of Engineering Materials, Vol. 17, N 12, pp. 1433-1444.

17) Bibby, M.J. and Goldak, J.A. "Weld Induced Camber in Structural Sections." Weldments: Physical Metallurgy and Failure Phenomena. Proceedings of the Fifth Bolton Landing Conference, August 1978, Cristoffel, R.J. et al. (eds.), ISBN 0-931690-07-2, General Electric Company, Schenectady, NY, 12305, pp. 101-115, 1979.

18) Biggs, W.D. (1960). The Brittle Fracture of Steel. London: MacDonald and Evans LTD.

19) Bjorhovde, R., J. Brozetti, G.A. Alpsten, and L. Tall. (1972) Residual Stresses in Thick Welded Plates. Welding Journal, Vol. 51, Research Supplement, pp. 392-s to 405-s.

20) Blodgett, O. (1976, March) Distortion (Part III). Canadian Welder and Fabricator, p. 15.

21) Bloom, J.M. and J.L. Sanders. (1966). The Effect of a Riveted Stringer on the Stress in a Cracked Sheet. Journal of Applied Mechanics, Vol 33 , pp. 561-570.

22) Broek, D. (1987). Elementary Fracture Mechanics. 4th ed. Dordrecht, Netherlands: Martinis Nijhoff Publishers.

23) BSI. Guidance on the Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures, PD6493: 1991. British Standards Institution (BSI): 1991.

24) Bucci, R.J. Effect of Residual Stress on Fatigue Crack Growth Rate Measurement. Fracture Mechanics: Thirteenth Conference. ASTM STP 743. Ed. Richard Roberts. American Society for Testing and Materials, 1981. pp. 28-47.

25) Burnside, O.H. et al. Long-Term Corrosion Fatigue of Welded Marine Steels. SSC-326. Washington, D.C.: Ship Structure Committee, 1984.

26) Cartwright, D.J. and T.P. Rich. Plastic Strip Yielding for a Crack in a Stiffened Sheet. First Intl. Conf. on Numerical Methods in Fracture Mechanics, 1978. University College, Swansea.

27) Clayton, A.M. (1993). Design of Welded Structures to Avoid Fracture and Plastic Collapse. Welding in the World, Vol 32, pp. 25-32.

28) Columbi, P., and Dolinski, K. Fatigue Reliability under Stochastic Load. Safety and Reliability, Proc. 1995 OMAE Conference. ASME, 1995. pp. 207-214.

29) Cook, R., S. Dorey and D.P. Rooke. A Computer Program to Calculate Growth Rates for Cracks at Notches in Regions of Residual Stress. Tech. Memorandum Materials and Structures 1207. Farnborough, England: Defence Research Agency, 1992.

30) Cramer, E. et al. Fatigue Assessment of Ship Structures. DNV Report No. 93-0432, N-1322. HOVIK, DNV: Division Ship and Offshore, Norway, 1994.

31) Dalzell, J.F., N.M. Maniar, and M.W. Hsu. Examination of Service and Stress Data of Three Ships for Development of Hull Girder Load Criteria. SSC-287. Washington, D.C.: Ship Structures Committee, 1979.

32) Demsetz, Laura. Optimal Strategies for Inspection of Ships for Fatigue and/or Corrosion Damage. Ship Structure Committee, Project SR-1365. Interim Report of U.C. Berkeley, 1997.

33) Dexter, R.J. and Fisher, J.W. "Fatigue and Fracture." Steel Design Handbook: LRFD Method, Ed. A.R. Tamboli. New York, New York: McGraw Hill, 1997. pp. 8-1 to 8-53.

34) Dexter, R.J., J.W. Fisher, and J.E. Beach. Fatigue Behavior of Welded HSLA-80 Members. 12th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), 1993: ASME.

35) Dexter, R.J. and M.L. Gentilcore. Evaluation of Ductile Fracture Models for Ship Structural Details. SSC-393. Washington, D.C.: Ship Structure Committee, 1996.

36) Dexter, R.J., S.J. Hudak, and D.L. Davidson. (1989). Modeling and Measurement of Crack Closure and Crack Growth Following Overloads and Underloads. Engineering Fracture Mechanics, Vol 33, N 6, pp. 855-870.

37) Dexter, R.J, E.B. Norris, W.R. Schick, and P.D. Watson. Performance of Underwater Weldments. SSC 335. Washington, D.C.: Ship Structure Committee, 1990.

38) Dexter, Robert J. and Pilarski, P. J. Growth and Instability of Large Cracks in Redundant Structures. Proceedings of the 12th Engineering Mechanics Conference, ASCE, 17-20 May 1998. La Jolla, CA: ASCE, 1998.

39) Dexter, R.J., A. Pellissier-Tanon, D. Pont, C.-P. Leung, and M. Behravesh. Residual Stress Analysis of Reactor Pressure Vessel Attachments. International Conference on Residual Stresses (ICRS3), Osaka, Japan, July 20-24, 1991.

40) Dexter, R.J., A. Pellissier-Tanon, D. Pont, C.-P. Leung, and M. Behravesh, The Use of Residual Stress Analysis in Reactor Pressure Vessel Attachments. Presented at the Structural Mechanics in Reactor Technology (SMiRT 11), Post-Conference Seminar (PCS) 2, Taipei, August 26-28, 1991.

41) Dexter, R.J., C.-P. Leung, and D Pont. Residual Stress Analysis in BWR Pressure Vessel Attachments, Electric Power Research Institute Report EPRI TR-1--651, Project C102-3, June 1992.

42) Dexter, R.J., S.C. Grigory, and W.R. Schick. Residual Stress and Deformation Prediction in Welded Structural Components. SwRI Internal Research Project 06-9497, Final Report, July 1989.

43) Dobson, W.G., et al. Fatigue Considerations in View of Measured Load Spectra. SSC-315. Washington, D.C.: Ship Structures Committee, 1982.

44) Dugdale, D.S. (1960). Yielding of Steel Sheets Containing Slits. J. Mech. Phys. Solids, Vol 8 , N 2 , pp. 100-104.

45) Elber, W. (1970). Fatigue Crack Closure under Cyclic Tension. Engineering Fracture Mechanics, Vol 2, pp. 37-40.

46) Ellyin, F. (1997). Fatigue Damage, Crack Growth and Life Prediction. (1st ed.) London: Chapman and Hall.

47) Engle, R.M. Damage Accumulation Techniques in Metallic Structures: Analysis Methods and Applications. STP 842. Philadelphia, PA: ASTM, 1984.

48) Faulkner, D. (1975, March). A Review of Effective Plating for Use in the Analysis of Stiffened Plating in Bending and Compression. Journal of Ship Research, Vol. 19, N 1, pp. 1-17.

49) Faulkner, D. Compression Tests on Welded Eccentrically Stiffened Plate Panels. Steel Plate Structures. Ed. P.J. Dowling et al., Crosby Lockwood. pp. 581-617.

50) Faulkner, D., et al. (1993). Synthesis of Welded Grillages to Withstand Compression and Normal Loads. Great Britain: Permagon Press. Computers and Structures, Vol 3, pp. 221-246.

51) Finch, D.M. and F.M. Burdekin. (1992). Effects of Welding Residual Stresses on Significance of Defects in Various Types of Welded Joints. Engineering Fracture Mechanics, Vol 41 , N 5 , pp. 721-735.

52) Fisher, J.W., K.H. Frank, M.A. Hirt, and B.M. McNamee. Effect of Weldments on the Fatigue Strength of Steel Beams. Washington, D.C.: National Cooperative Highway Research Program (NCHRP) 102, Highway Research Board, 1970.

53) Fisher, J.W., et al. Phase I: Final Report--Development of Advanced Double Hull Concepts. TDL 91-01 Phase 1.3(a). Philadelphia, PA: ATLSS/FFP and U.S. Navy MANTECH, Fleet of the Future Program, 1993.

54) Fisher, J.W., et al. Fatigue Strength of Steel Beams with Welded Stiffeners and Attachments. Washington, D.C.: National Cooperative Highway Research Program (NCHRP) 147, Transportation Research Board, 1974.

55) Fisher, J.W., et al. Resistance of Welded Details Under Variable Amplitude Long-Life Fatigue Loading. National Cooperative Highway Research Program Report 354. Washington, D.C.: Transportation Research Board, 1993.

56) Fitzpatrick, M.E., and L. Edwards. (1998). Fatigue Crack/Residual Stress Field Interactions and Their Implications for Damage Tolerance Design. JMEPEG, Vol 7, pp. 190-98.

57) Formby, C.L., and J.R. Griffiths. The Role of Residual Stresses in the Fracture of Steel. Proceedings of the International Conference "Residual Stresses in Welded Construction and Their Effects," 15-17 November 1977, London, The Welding Institute, Abington Hall, Abington, Cambridge, CB1 6AL, UK, pp. 359, 1977.

58) Francis, P.H., J. Lankford, Jr., and F.F. Lyle, Jr. (1976, April) Subcritical Crack Growth and Ship Structural Design. Marine Technology, Vol 13, N 2, pp.152-160.

59) Freudenthal, A.M. and M. Shinozuka. On Fatigue Failure of a Multiple-Load-Path Redundant Structure. First Intl. Conf. on Fracture, 1965. Sendai, Japan: Jpn Soc. for Strength and Fracture of Materials, 1965.

60) Galambos, T.V., Guide to Stability Design Criteria for Metal Structures. 4th ed. NY: Wiley-Interscience, 1988.

61) Garwood, S.J., R.H. Leggat, and T. Ingham. (1994). Structural Collapse, The Failure Assessment Diagram and "Off-The-Shelf" Operation. Fatigue and Fracture of Engineering Materials, Vol 17 , N 12 , pp. 1418-1431.

62) Ghassem, Mansoor Mohammad. “Fracture Diagram for Stiffened Panel and Computer Based Approach for Structural Life Prediction.” Ph.D. Dissertation: Mechanical Engineering. Texas A&M University: College Station, 1980.

63) Goldak, J., et al. Progress in Computing Residual Stress and Strain in Welds. “Advances in Welding Science and Technology”, TWR '86. International Conference on Trends in Welding Research, Gatlinburg, Tennessee, USA. 18-22 May, 1986.

64) Grief, R. and J.L. Sanders, Jr. (1965). The Effect of a Stringer on the Stress in a Cracked Sheet. J. of Applied Mechanics, Series E, Vol 32 , N 1, pp. 647-665.

65) Gurney, T.R. Comparative Fatigue Tests on Fillet Welded Joints under Various Types of Variable Amplitude Loading in Air. 12th Intl. Conf. on OMAE, 1993: ASME, 1993.

66) Hahn, G.T., and M. Sarrate. Failure Criteria for Through-Cracked Vessels. “Practical Fracture Mechanics for Structural Steel.” Proc. of the Symposium on Fracture Toughness Concepts for Structural Steel, April 1969. Ed. M.O. Dobson. Risley, U.K.:U.K. Atomic Energy Authority, 1969.

67) Hibbitt, H.D. and Pedro V. Marcal. (1972). A Numerical Thermo-Mechanical Model for the Welding and Subsequent Loading of a Fabricated Structure. Computers & Structures, Vol. 3, pp. 1145-1174.

68) Hoffman, D., Walden, D.A., and M.E. Wojnarowski. Environmental Wave Data for Determining Hull Structural Loadings. SSC 268. Washington, D.C.: Ship Structures Committee, 1979.

69) Hollister, S.C., J. Garcia, and T.R. Cuykendahl. Fatigue Tests of Ship Welds. Washington, D.C.: Ship Structure Committee, SSC-7, 1946.

70) Hollister, S.C., J. Garcia, and T.R. Cuykendall. Final Report on Fatigue Tests in Ship Welds. Washington, D.C.: SSC-14, Ship Structure Committee, 1948.

71) Horne, M.R., and R. Narayanan. (1976). The Strength of Straightened Welded Steel Stiffened Plates. The Structural Engineer, Vol 54, N 11, pp. 437-43.

72) Horne, M.R., P. Montague, and R. Narayanan. Influence on Strength of Compression Panels of Stiffener Section, Spacing, and Welded Connection. Proc. of the Institute of Civil Engineers, Part 2, 1977a. p. 63.

73) Irwin, G.R. (1957). Analysis of Stresses and Strains near the End of a Crack Traversing a Plate. Journal of Applied Mechanics, Vol 24 , pp. 361-364.

74) Isida, M. (1966). Stress Intensity Factors for the Tension of an Eccentrically Cracked Strip. Trans. ASME, J. Applied Mechanics, Vol 33, p. 674.

75) Isida, M. (1970). On the Determination of Stress Intensity Factors for Some Common Structural Problems. Eng. Fract. Mech., Vol 2 , pp. 61-69.

76) Isida, M. (1973). Analysis of Stress Intensity Factors for the Tension of a Centrally Cracked Strip with Stiffened Edges. Engineering Fracture Mechanics, Vol 5, pp. 647-665.

77) Itoh, Y.Z., S. Suraga, and H. Kashiwaya. (1989). Prediction of Fatigue Crack Growth Rate in Welding Residual Stress Field. Engineering Fracture Mechanics, Vol 33, N 3, pp. 397-407.

78) Jan, H.-Y., K.-T. Chang, and M.E. Wojnarowski. Comparison of Stresses Calculated Using the Daisy System to Those Measured on the SL-7 Containership Program. SSC-282. Washington, D.C.: Ship Structures Committee, 1979.

79) Jiao, Guoyang. Reliability Analysis of Crack Growth with Inspection Planning. OMAE, Vol 2 , 1992: pp. 227-235.

80) Jordan, C.R. and L.T. Knight. Further Survey of In-Service Performance of Structural Details. SSC –294. Washington, D.C.: Ship Structure Committee, 1980.

81) Jordan, C.R. and R.P. Krumpen, Jr. Design Guide for Ship Structural Details. SSC-331. Washington D.C.: Ship Structure Committee, 1985.

82) Kaczinski, M.R., R.J. Dexter, and JP. Van Dien. Fatigue-Resistant Design of Cantilevered Signal, Sign and Light Supports. NCHRP Report 412. Washington, D.C.: National Cooperative Highway Research Program, 1998.

83) Kamtekar, A.G. (1978). The Calculation of Welding Residual Stresses in Thin Steel Plates. Int. J. Mech. Sci., Vol 20, pp. 207-227.

84) Kim, S.C., Y. Fujimoto, and E. Shintaku. Study on Fatigue Reliability and Inspection of Ship Structures Based on Questionnaire Information. PACOMS, 1996.

85) Kinoshita, M., K. Kono, and K. Shingai. (1973). Estimation of Fatigue Crack Propagation Life of Steel Plates and of Structural Member Model of Ship Hull. Engineering Fracture Mechanics, Vol 5, pp. 563-584.

86) Kishima, Y., G.A. Alpsten, and L. Tall. Residual Stresses in Welded Shapes of Flame Cut Plates in ASTM A572(50) Steel. Fritz Laboratory Report No. 321.2. Bethleham, PA: Lehigh University, 1969.

87) Kondo, J., and A. Ostapenko. Tests on Longitudinally Stiffened Plate Panels with Fixed Ends—Effect of Lateral Loading. Report No. 248.12. Fritz Engineering Laboratory, 1964.

88) de Koning, A.U. A Simple Crack Closure Model for the Prediction of Fatigue Crack Growth Rates Under Variable-Amplitude Loading. Fracture Mechanics: Thirteenth Conference. ASTM STP 743. Ed. Richard Roberts. American Society for Testing and Materials, 1981. pp. 63-85.

89) Kujawski, D., and F. Ellyin. (1984). A Fatigue Crack Propagation Model. Engineering Fracture Mechanics, Vol 20, N 5/6, pp. 695-704.

90) Lambrigger, M. (1997, February). Weibull Master Curves, Residual Stress Fields and Stable Crack Growth. J. Materials Science Letters, Vol 16, N 4, pp. 298-300.

91) Larrson, L.H. Subcritical Crack Growth Due to Fatigue, Stress Corrosion and Creep. New York: Elsevier Applied Sciences Publishers, 1984.

92) Leggat, R.H. Fracture Assessment in the Presence of Residual Stresses. England: The Welding Institute: Cambridge, 1984. pp 1239-1246.

93) Leggatt, R.H. Residual Stresses at Girth Welds in Pipes. Proceedings of the International Conference "Welding in Energy-Related Projects," 20-21 September 1983, Toronto, pp. 429-439.

94) Leggatt, R.H. and J.D. White. Predicting Shrinkage and Distortion in a Welded Plate. Proceedings of the International Conference "Residual Stresses in Welded Construction and Their Effects," 15-17 November 1977, London, The Welding Institute, Abington Hall, Abington, Cambridge.

95) Leung, C.K. and R.J. Pick. The Use of Generalized Plane Strain Elements in The Prediction of Residual Stresses in Welded Flat Plates. Symposium on Computer Modelling of Fabrication Processes and Constitutive Behavior of Metals, Ottawa, Canada, May 25-16, 1986, Too, J. (ed.), CANMET, Ottawa. pp. 563-585.

96) Leung, C.K. and R.J. Pick. Finite Element Analysis of Multi-Pass Welds. Bulletin 356. Welding Research Council Bulletin, August 1990. pp. 11-33.

97) Liu, D. and Thayamballi, A. Local Cracking in Ships--Causes, Consequences, and Control. Workshop and Symposium on the Prevention of Fracture in Ship Structure. 1995. Washington, D.C.: Marine Board, Committee on Marine Structures, National Research Council.

98) Maddox, S.J. Fatigue Strength of Welded Structures. 2nd ed. Cambridge, U.K.: Abington Publishing, 1991.

99) Mansour, Alaa E. Gross Panel Strength Under Combined Loading. SSC 270. Washington, D.C.: Ship Structures Committee, 1977.

100) Mansour, A., et al. Assessment of Reliability of Existing Ship Structures. SSC-398. Washington, D.C.: Ship Structure Committee, 1997.

101) Mansour, Alaa. (1972, June) Methods of Computing the Probability of Failure Under Extreme Values of Bending Moment. J. Ship Research, pp. 113-123.

102) Marine Digest and Transportation News. March, 1998

103) Miner, M.A. (1945) Cumulative Damage in Fatigue. Journal of Applied Mechanics, Vol. 12, 1945: p. A-159.

104) Murakami, Y., et al. Stress Intensity Factors Handbook. Oxford, U.K.: Permagon Press, 1987.

105) Murray, N.W. (1975). Analysis and Design of Stiffened Plates for Collapse Load. The Structural Engineer, Vol 53, N 3, pp. 153-8.

106) Nagaraja Rao, N.R., and Tall, L. (1961). Residual Stresses in Welded Plates. Welding Journal, Vol. 40, Research Supplement, pp. 468-s to 480-s.

107) National Research Council. Marine Board. Committee on Marine Structures. Prevention of Fracture in Ship Structure. Proc. of the Symposium and Workshop on the Prevention of Fracture in Ship Structure. 30-31 March 1995. Washington, D.C.: National Research Council, 1997.

108) Newman, J.C. Jr. A Crack-Closure Model for Predicting Fatigue Crack Growth Under Aircraft Spectrum Loading, Technical Memo 81941, NASA, 1981.

109) Nussbaumer, Alain. "Propagation of Long Fatigue Cracks in Multi-Cellular Box Beams." Ph.D. dissertation in Civil Engineering, 1993. Bethlehem, Pennsylvania: Lehigh University.

110) Nussbaumer, A.C., R.J. Dexter, J.W. Fisher, and E.J. Kaufmann, Propagation of Very Long Fatigue Cracks in a Cellular Box Beam, Fracture Mechanics,

Twenty-Fifth Volume, ASTM STP 1220, F. Erdogan and Ronald J. Hartranft, Eds., American Society for Testing and Materials, Philadelphia, pp.518-532, 1994.

111) A.C. Nussbaumer, J.W. Fisher, and R.J. Dexter. (1998). Behavior of Long Fatigue Cracks in a Cellular Box Beam. Submitted for review to ASCE Journal of Structural Engineering, 1998.

112) Ogeman, Rutger T., B. Josefson, and Anders Ulfarson. (1995). Residual Stresses at a Longitudinal Stiffener--Web Frame Intersection and Their Effects on Crack Growth. Marine Structures, Vol 8 , pp. 603-616.

113) Ohji, K, et al. (1987). Methods of Predicting Fatigue Crack Growth Lives in Residual Stress Fields. Trans. Japanese Soc. Mech. Eng., Vol 53 , N 492, p. 1516.

114) Osgood, William R. Residual Stresses in Metals and Metal Construction. New York:Reinhold Publishing Corp. Prepared for the Ship Structure Committee, 1954.

115) Pang, A.A.-K., R. Tiberi, L.-W. Lu, J.M. Ricles, and R.J. Dexter. (1995, February) Measured Imperfections and Their Effects on Strength of Component Plates of a Prototype Double Hull Structure. Journal of Ship Production, Vol. 11, No. 1, pp. 47-52.

116) Pang, H.L.J. A Linear Elastic Fracture Mechanics Assessment of the Fatigue-Crack-Growth Behaviour for a Semi-Elliptical Surface Crack in Machined and Welded Specimens Subjected to Constant Amplitude Tension Loading. Dept.of Trade and Industry. National Engineering Laboratory, 1991.

117) Paris, P. and F. Erdogan. (1963). A Critical Analysis of Crack Propagation Laws. Trans. ASME, Ser. D. Journal of Basic Engineering, Vol 85 , N 4, pp. 528-534.

118) Petershagen, H. (1986). Fatigue Problems in Ship Structures. Advances in Marine Structures. London: Elsevier Applied Science, pp 281-304.

119) Petershagen, H. (1993). Stress Analysis and Fatigue Life Prediction of Ship Structures. Welding in the World, Vol 32, pp.75-82.

120) Petershagen, H., and Fricke, W. Fatigue Crack Propagation in Plate Panels with Welded Stiffeners. IIW-Doc. XIII-1272-88. Technical University of Hamburg Harburg, 1988.

121) Pisarski, H.G. and S. Slatcher. Assessment of the Significance of LBZ's in Steels Using a Probabilistic Model. OMAE, Vol 2 , 1993: pp. 89-97.

122) Poe, Clarence C. "The Effect of Riveted and Uniformly Spaced Stringers on the Stress Intensity Factor of a Cracked Sheet." M.S. Thesis: Mechanical Engineering. Virginia Polytechnic Institute, 1969.

123) Poe, C.C., Jr. Fatigue Crack Propagation in Stiffened Panels. ASTM STP 486. 1971: ASTM.

124) Rampetstreiter, R.H., T. Lee, and A. Ostapenko. Tests on Longitudinally Stiffened Plate Panels—Effect of Residual Stresses and Rotational Restraint by Stiffeners. Report No. 248.5. Fritz Engineering Laboratory, 1962.

125) Ratwani, M.M. (1978). A Parametric Study of Fatigue Crack Growth Behavior in Adhesively Bonded Metallic Structures. Trans. ASME, Vol 77, pp. 1-6.

126) Reemsnyder, H.S. Fatigue and Fracture of Ship Structures. Symposium on the Prevention of Fracture in Ship Structure. 30-31 March 1995. Washington, D.C.: Marine Board, Committee on Marine Structures, National Research Council.

127) Riemelmoser, F.O. and R. Pippan. (1997). Crack Closure: A Concept of Fatigue Crack Growth under Examination. Fatigue and Fracture of Materials and Structure, Vol 20, N 11, pp. 1529-1540.

128) Rolfe, S.T. Fracture Mechanics, Fracture Criteria and Fracture Control for Welded Steel Ship Hulls. Report 244. Washington, D.C.: The Society of Naval Architects and Marine Engineers, 1974.

129) Rolfe, S.T., K.T. Hays, and A.E. Henn. Fracture Mechanics Methodology for Fracture Control in VLCC's. Ship Structures Symposium, 1993. Arlington, VA: SNAME and SSC.

130) Rolfe, S.T., D.M. Rhea, and B.O. Kuzmanovic. Fracture Control Guidelines for Welded Steel Ship Hulls. SSC-244. Washington, D.C.: Ship Structures Committee, 1974.

131) Rooke, D.P. and D.J. Cartwright. Compendium of Stress Intensity Factors. Uxbridge, Middex, U.K.: Hillington Press, 1976.

132) Rybicki, E.F., et al. (1988). Experimental and Computational Residual Stress Evaluation of a Weld Clad Plate and Machined Test Specimens. Journal of Engineering Materials and Technology, Vol. 110, pp. 297-304.

133) Rybicki, E.F., and R.B. Stonesifer. An Analysis Procedure for Predicting Weld Repair Residual Stresses in Thick Walled Vessels. Pressure Vessels and Piping Conference, 25-29 June 1979. San Francisco, California: ASME,1979.

134) Salvetti, A. and A. Del Puglia. Fatigue Crack Propagation in Stiffened Panels. The Eighth Congress of the International Council of the Aeronautical Sciences, 1972. Amsterdam, The Netherlands: AIAA, 1972.

135) Sanders, J. Jr. Effect of a Stringer on the Stress Concentration Due to a Crack in a Thin Sheet, Technical Report R-13, NASA, 1959.

136) Sih, G.C. and Faria, L. (1984). Fracture Mechanics Methodology. Martinus Nijhoff Publishers, The Hague, Netherlands.

137) Sikora, J.P., A. Dinsenbacher, and J.E. Beach. (1983, May). A Method for Estimating Lifetime Loads and Fatigue Lives for SWATH and Conventional Monohull Ships. Naval Engineers Journal, pp. 63-85.

138) Smith, C.S. (1975). Compressive Strength of Welded Steel Ship Grillages. Transactions RINA, Vol 117, pp. 325-359.

139) Soares, G. and Y. Garbatov. Influence of Inspection and Repair on the Fatigue Reliability of Oil Tankers. OMAE, Vol 2, 1996: pp. 245-254.

140) Solin, J. Analysis of Spectrum Fatigue Tests in Sea Water. Ninth Intl. Conf. on OMAE Symposium, 1990. New York, NY, USA: ASME.

141) Stenseng, Arne. (1996). Cracks and Structural Redundancy. Marine Technology, Vol 33, N 4, pp. 290-298.

142) Sumi, Yoichi, Hisashi Iyama, Zeljko Bozic, and Yasumi Kawamura. (1996), Multiple Fatigue Cracks Propagating in a Stiffened Panel. Journal of the Society of Naval Architects of Japan, Vol 179, pp. 407-412.

143) Swift, T. The Effects of Fastener Flexibility and Stiffener Geometry on the Stress Intensity Factor for a Stiffened Cracked Sheet. Intl. Conf. on Prospects of Fracture Mechanics, 1974. Noordoff, Leyden, The Netherlands: Delft Univ. of Tech., 1974.

144) Swift, T. Fracture Analysis of Adhesively Bonded Cracked Panels. Transactions of the American Society of Mechanical Engineers, 1978. Atlanta, GA: ASME, 1978.

145) Tada, H. (1985). The Stress Analysis of Cracks Handbook. Saint Louis: Paris Productions, Inc.

146) Tall, L. (1964, January). Residual Stresses in Welded Plates--A Theoretical Study. Welding Journal, Research Supplement, 10s-23s.

147) Tall, L., and G.A. Alpsten. On the Scatter in Yield Strength and Residual Stress in Steel Members. Symposium on Concepts of Safety of Structures and Methods of Design. September 1969. London: International Association for Bridge and Structural Engineering, pp. 151-163.

148) Tanaka, K. Mechanics and Micromechanics of Fatigue Crack Propagation. 20th Symposium on Fracture Mechanics: Perspectives and Directions, 1989. Philadelphia, PA: ASTM.

149) Tanker Structure Co-operative Forum. Int'l Chamber of Shipping and Oil Companies Int'l Marine Forum. Guidance Manual for the Inspection and Condition Assessment of Tanker Structures. London, England: Witherby & Co., Ltd., 1986.

150) Tanker Structure Co-operative Forum. Int'l Chamber of Shipping and Oil Companies Int'l Marine Forum. Guidelines for the Inspection and Maintenance of Double Hull Tanker Structures. London, England: Witherby & Co., Ltd., 1995.

151) Tanker Structure Co-operative Forum. Condition Evaluation and Maintenance of Tanker Structures. London, England: Witherby & Co., Ltd., 1992.

152) Terada, H. Stress Analysis of a Crack in the Residual Stress Field by Welding and Its Application to the Fatigue Crack Propagation. Tokyo, Japan: National Aerospace Laboratory, 1994.

153) Tebedge, N., and L. Tall. Residual Stresses in Structural Steel Shapes: A Summary of Measured Values. Fritz Laboratory Report No. 337.34. Bethleham, PA: Lehigh University, 1973.

154) Thayamballi Mathummal, Anil Kumar. "Reliability of Ship Hull in the Fracture and Fatigue Modes of Failure." Ph.D. dissertation in Engineering. 1983. University of California, Berkeley.

155) Torii, Tashiyuki; Kazuo Honda, and Masahiko Sugiyam. (1989). Surface Fatigue Crack Propagation Behavior in a Residual Stress Field. JSME International Journal, Vol 32, N 3, pp. 450-457.

156) Torii, T., K. Honda, and T. Hamano. (1988). Fatigue Crack Propagation Behavior in a Tensile Residual Stress Field. Trans. Japan Soc. Mech. Eng., Vol 54, N 500, pp. 679.

157) Toyosada, Masashiro; Toshio Niwa and Junichi Sakai. (1997). Physical Meaning of Delta KRP and Fatigue Crack Propagation in the Residual Stress Distribution Field. International Journal of Fatigue, Vol 19 , Suppl. 1, pp. S161-S166.

158) Toyosada, Masahiro and Toshio Niwa. (1995). Fatigue Crack Propagation Behavior in the Field of Residual Stress Distribution: Study of Fatigue Crack Propagation Based Upon RPG Load (7th Report). Journal of the Society of Naval Architects of Japan, Vol 178 , pp. 505-511.

159) Troitsky, M.S. Stiffened Plates: Bending, Stability and Vibrations. Oxford: Elsevier Scientific Publishing Co., 1976.

160) Ueda, Y., K. Fukuda, and K. Nakacho. Basic Procedures in Analysis and Measurement of Welding Residual Stresses by the Finite Element Method. Proceedings of the International Conference "Residual Stresses in Welded Construction and Their Effects," 15-17 November, 1977, London, The Welding Institute: Abington Hall, Abington, Cambridge, CB1 6AL, UK.

161) Ueda, Y. and K. Nakacho. (1982). Simplifying Methods for Analysis of Transient and Residual Stresses and Deformations Due to Multipass Welding. Transactions of JWRI, Vol. 11 (1), pp. 95-103.

162) Ueda, Y. and H. Murakawa. (1984). Applications of Computer and Numerical Analysis Techniques in Welding Research. Transactions of JWRI, Vol. 13, No. 2, pp. 337-346.

163) U.S. Coast Guard. Circular 15-91. USCG NVIC 15-91. Washington, D.C.: U.S. Coast Guard, 1991.

164) Vlieger, H. (1973). The Residual Strength Characteristics of Stiffened Panels Containing Fatigue Cracks. Engineering Fracture Mechanics, Vol 5, N 2, pp. 447-477.

165) Vroman, R.H. An Analysis into the Uncertainty of Stiffened Panel Ultimate Strength. Trident Report 234. Annapolis, MD: U.S. Naval Academy, 1995.

166) Watanabe, M., H. Yajima, and H. Kawano. (1979). Analysis of the Crack Strength of a Stiffened Panel in a Ship Hull Structure. J. Soc. Naval Arch. Japan, Vol 146, pp. 314-320, 530.

167) White, J.D. and J.B. Dwight. Weld Shrinkage in Large Stiffened Tubulars. Proceedings of the International Conference "Residual Stresses in Welded Construction and Their Effects", 15-17 November 1977. London: The Welding Institute, Abington Hall, Abington, Cambridge, CB1 6AL, UK, Paper 21. pp. 337-344.

168) Winter, P.W., and Macinnes, Don A. Fatigue under Variable Amplitude Loading: A New Approach. ”Safety and Reliability”, Proc. 1993 OMAE Conference. ASME, 1993. pp. 99-106.

169) Xiao, Dayton and R.J. Dexter. (1998). Finite Element Calculation of Applied J-Integral for Cracked Ship Structural Details. Engineering Fracture Mechanics, Vol 60, N 1, pp. 58-82.