REPORT DOCUMENTATION PAGE

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<td>N00014-96-1-0631</td>
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<tr>
<td>A New Approach to Structural Reliability in Fatigue Failure</td>
<td>Dr. Sia Nemat-Nasser (PI) Dr. Joseph Zarka</td>
<td>97PR01513-00</td>
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<td>University of California, San Diego Dept. of MAE 9500 Gilman Drive La Jolla, CA 92039-0416</td>
<td>Office of Naval Research Program Officer Rosynd S. Barsoum ONR 334 Ballston Centre Tower One 800 North Quincy Street, Arlington, VA 22217-5660</td>
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<td>structural reliability, fatigue failure, welded structures</td>
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<td>The project objective is to develop formalism for assessing fatigue fracture of welded parts of ship structures based on a newly developed automatic Learning Expert System (L.E.S.), using extensive knowledge of material characteristics, experimental results, and results obtained through computational simulations. Any study of the welds on a ship structure must take into account the uncertainties and random characteristics of the loading, as well as the fatigue lifetime of the welds. Due to the stochastic nature of the loads, the available deterministic approaches are not sufficient to give a reliable evaluation of the structural safety. Although there has been some effort to fill this gap by probabilistic approaches, these are yet of limited usefulness because of the limited available databases. The research project will ultimately demonstrate the applicability and effectiveness of L.E.S to this class of engineering mechanics problems. As the first and fundamental step in this project, it is necessary to build a relevant database. Experimental and field data has secured from Navy research centers, and through collaboration with scientists working in this general area. Additional data has been obtained from literature searches.</td>
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Enclosure 1

Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18
239-102
FINAL TECHNICAL REPORT

New Approach to Structural Reliability in Fatigue Failure

Period: April 1996 - February 2002
Contract No: N00014-96-1-0631
ONR Program Officer: Roshdy Barsoum

PI: Sia Nemat-Nasser
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Center of Excellence for Advanced Materials
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Submitted: August 15, 2002
I. Abstract

The features of welded joints not only shorten their service lives, but also make modeling of their fatigue damage complicated. Our research approach utilized the automatic learning technology to make the best use of available information in the assessment of structural reliability. Our goal was to build tools for assessing and predicting fatigue/failure of structures, in particular the welded ship structures. Considerable progress has been made, albeit further improvement can be achieved.

At first, we built an organized database of experimental data and numerical analysis results that includes the possibly governing parameters in failure process. Then we extracted the mathematical relations between these parameters from the database using various automatic learning tools in a systematic way, and checked their predictive accuracy. After the mathematical relations became reliable, we applied them to new data sets to predict fatigue failure likelihood and life expectancy. This approach can be extended to new problems, and can be used to provide clues for further study of failure mechanisms.

We developed specific procedures and applied them to cruciform and beam structural details made of welded A36 steel and AL-6XN stainless steel components. To ensure the validity of the approach, different geometric configurations and materials were included. Parameters of fatigue damage, including geometry, material properties, loading history and stress field under the loading, were either collected from experimental records or generated using finite element analysis for the critical positions in the structural details. We employed a window of optimal size and focused it over the structure, wherever failure might occur. Inside the window, factors such as equivalent range of applied loading, maximum, minimum and average value of von Mises stress as well as contours of constant stresses and their spatial gradients were computed. These parameters were then put together with the recorded fatigue failures and the data sets were submitted to a comprehensive automatic learning system to extract the imbedded mathematical patterns. The obtained rules, neural networks, and statistical regression functions delivered fairly accurate predictions of dangerous areas and yielded projected fatigue lives that can be used as lower and upper bounds of the actual fatigue lives.

II. Technical Section

Research Objective

A new approach based on automatic learning and optimization techniques was used to study the reliability of ship structures and particularly the fatigue failure of the welded parts. The automatic learning technology made it possible to integrate the available knowledge of experts with the experimental results and/or numerical simulation results. The goal was to systematically build a tool for assessing and predicting fatigue/failure of any part, especially weldments, of large structures subjected to any loading, through sub-structuring and using experimental database as well as computational/theoretical analyses in a unified manner. This goal has been realized to the degree that the available data permit.

Science & Technology Objective

As to our specific technological development, we have used laboratory experimental data on specific welded details for ship structures, together with systematic computational simulations, to develop mathematical formulas in terms of rules, weights and regression functions to predict whether or not given structural details, subjected to pseudo random design loading, would fail and have estimated the corresponding life expectancy. Our research work included different geometric configurations such as cruciform specimens and beams, and different materials including the stainless steels for future naval constructions. This approach delivered fairly accurate predictions of dangerous areas and yielded projected fatigue lives that can be used as lower and upper bounds of the actual fatigue lives. This
approach can be used to predict fatigue failure and the corresponding life of other details and large structures, and can be improved as more data become available.

Technical Approach I (Database Construction)

Several fatigue tests have been utilized in our approach. The first one was carried out at University of Illinois at Urbana-Champaign to investigate the Fatigue Characterization of Fabricated Ship Details for Design (ship structure committee report SSC-346). Experiments were performed on a typical structure using a variable load history that simulated a ship history. The selected structural detail, ship structural detail No. 20, is often used in ship and offshore structural design, and is one of the more fatigue-prone structural components. The detail No. 20 consists of a central plate and two long loading plates welded to the central plate by all-around Shielded Metal Arc Welding (SMAW) fillet welds (see figure 1). Subsequently, three experimental resources have been used to expand the scope of database. They are:


2. Fatigue Strength of Stainless Steel Weldments in Air, D.P. Kihl et al; Naval Surface Warfare Center, Carderock Division, (NSWCCD-65-TR-2000/04)

3. Fatigue Resistance of Large Welded AL-6XN Stainless Steel Components with Fillet, Groove and Attachment Welds, I.W. Fisher et al; ATLSS Engineering Research Center, Lehigh University (ATLSS report 01-04).

The three experimental reports recorded fatigue tests on A36 steel beam, stainless steel cruciform, and stainless steel beam specimens, respectively. Basic configurations of the three experiments are shown in figure 2, 3, and 4, respectively.

Figure 1. Detail No. 20 sample (dimension in mm)
Figure 2. Schematic of A36 steel beam testing

Figure 3. Stainless steel cruciform specimen (dimension in inch)
Figure 4. Schematic of Stainless steel beam testing (dimension in inch)

Figure 5, below, shows the technical approach. The basic idea was to create a finite element model of the sample and try to simulate the material properties and initial state of the structure as close to the reality as possible. Afterward, the experimental records and numerical analysis results were put together, and a hybrid automatic learning system was used to extract the data patterns embedded in the database.
Fatigue Failure Data Resource
- Geometry
- Material Properties
- Stress Fields
- Load
- S-N curves
- Recorded Failure Data

Database of Physics-Based Descriptors
- Numerical Analysis Model
- Tensile/Cyclic Strength
- Stress Contours at Hot Points
- Loading History Data
- S-N Curve Constants
- Load Cycles at Failure

Consistent and Clear Format for All Data Sets

Automatic Learning Tools
- Multi-Layer Perceptron Network
- Probabilistic Neural Network
- Genetic Algorithms
- Statistical Analysis Software
- Group Method of Data Handling
- Learning Expert System
- Principal Components Analysis
- Other Automatic Learning Tools

Mathematical Relations between Descriptors
- In Forms of Polynomials, Rules, or Weights
- Use Independent Data Sets to Test Confidence Level

Results Satisfactory?

- Quantitative Representation of Knowledge about Fatigue Failure
- Prediction of Fatigue Failures for More Structures
- Classification Based on Probabilities of Structural Failure

Figure 5. The fundamental technical approach
For small specimens, 2-D numerical analysis was usually sufficient; but for large structures, it was necessary to do a general 3-D analysis at first, then make refine mesh around the critical zones. Once satisfactory finite element computation was done, a window with fixed size was used to tour around the model and collect data at the sites where cracking may occur (see Figure 6). A standard procedure for the construction of three-dimensional finite element models, sub-structuring of large structures and discreet representation of stress/strain contours has been developed, tested and refined. It will be continuously improved as we apply it to more samples.

Figure 6. The procedure to make mesh refinement and add windows around the hot points

Inside the windows, we computed the physics-based descriptors to describe the stress field, such as the first invariant $I_1$, the second invariant $J_2$ of the stress tensor and the gradient of $J_2$. We treated all cases in the same way, no matter whether it was a small specimen or a possible failure site in a large welded structure. Therefore, this approach is applicable to any structural reliability problem as long as the basic failure mechanism is the same. 724 data sets have been generated based on the experimental records and the numerical analyses.

**Technical Approach II (Results of Automatic Learning)**

After the data sets representing all the potential cracking sites were generated, the database was organized and submitted to an automatic learning system to extract the mathematical formulas. Several different automatic learning tools have been tested, compared, and combined in a systematic way to produce the best result. We found that the best way was to conduct a simple principal component analysis first to determine the proper mathematical dimensionality, then use learning expert system, neural networks, and statistical analysis software tools to investigate the database in parallel. Training of neural networks and statistical analysis software to predict fatigue life expectancy are shown in figures 7 and 8. The primary training base was the actual cracking failures recorded in the fatigue tests. After the training, we applied
the obtained formulas to all the data sets, and combined the results on the data sets from the same sample together to make the prediction for every specimen.

Figure 7. Predicted value vs. real value during training of a neural network
All data Life Regression Analysis — Use Log of Fatigue Life

\[ \log{cycle} = 22.672 - 0.0155 \log{stress} - 0.079 \log{stressu} + 0.9335 \log{stressy} + 0.0085 \log{11highmax} \\
+ 0.0068 J2highmax + 0.0012 gradJ2highmax + 0.0295 J1lowmax + 0.0065 J2lowmax \\
- 0.0015 gradJ2lowmax + 0.0071 J1lowave + 0.0595 \log{J2highave} \\
+ 0.0043 gradJ2highave + 0.0274 J1lowave + 0.0625 J2lowave + 0.0017 gradJ2lowwave \\
+ 0.0294 J1lowave + 0.0035 J1highmin + 0.0021 J2highmin - 0.0074 gradJ2highmin \\
+ 0.0048 J1lowmin + 0.0033 J2lowmin - 0.0224 gradJ2lowmin - 0.0248 J2lowin \]

**Figure 8.** Predicted value vs. real value during statistical analysis

Table 1 shows the results of identifying the more dangerous areas in structures. In this test, 200 data sets were randomly selected from the 724 data sets to train the learning expert system, and the rules correctly classified 99 of the 117 actual failures and 421 of the 607 actual non-failures.

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**Table 1.** Classification results for all available data sets

We computed both the minimum values and the average values of the projected fatigue lives generated on data sets from the same sample for all the samples we used. The results are shown in table 2. In most cases, the actual fatigue lives of the samples are between the minimum and the average predicted values. It has been observed that when the specimen was under a lot of distortion or induced bending, the minimum value is closer to the actual fatigue life of the specimen; when only a small amount of distortion or induced bending was present, the average value is closer to the actual fatigue life of the sample.

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and EOYFL July 1, 01- February 28, 02.
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Table 2. Predicted fatigue lives of the samples vs. the actual fatigue lives

It is notable that the predicted lives of A36 beams are quite accurate, and most of the predicted fatigue lives are conservative, but the predicted lives of AL-6XN stainless steel beams are not conservative. We interpret that it shows the finite element modeling of the stainless steel beams is not close enough to the actual testing conditions. This finding, however, demonstrates the self-correcting capability of this approach. It also demonstrates the necessity of closely monitored experimental work and highly tuned modeling to accurately simulate the damage process.
We are confident that, after some improvement, this method can be used as an effective way of computing lower and upper bounds for fatigue failure of structures with substantial crack initiation period.

**Impact/ Navy Relevance**

Ships consist of heavily welded structures that are regularly exposed to fluctuating loads during their service. Therefore, they are prone to metallic fatigue failure. Welds are of particular importance because they involve stress concentration and residual stresses. Therefore, they are likely to cause fatigue failure. Because of economic reasons, welding technique is widely employed in the construction of ships. This makes the study on fatigue of weld even more important.

Though some methods have already been developed, they generally require assumptions on the geometry, loading conditions, and material properties. Each calculation thus provides only numerical data for one particular case, which provides a limited basis for design decisions. The new approach, which we have used, offers a feasible way to avoid this major difficulty. It allows us to use all existing data, experimental, computational, or theoretical in a unified manner to support the design of structures. It also permits an interactive accumulation of available knowledge and uses the information effectively.

With hundreds of combat and supporting vessels operating in the seas around the world, it is very beneficial for the navy to have state-of-the-art tools to assess the reliability of welded ship structures. Not only can this help reducing the possibility of fatigue-fracture related accidents, but also it may lead to significant savings due to improved guidance of inspection-repair management. The importance of this problem is further reinforced by the fact that many navy ships are required to serve very long lives. The increasing usage of nuclear powered vessels also requires an even higher control over weld reliability due to the danger of potential nuclear leakage.

**III. Technology Transfer**

Through this project, we have been interacting with researchers from Naval Surface Warfare Center, particularly working with Dr. David Kihl. We have also been interacting with the researchers from Lehigh University's ATLSS center. In addition, we have been collaborating research efforts with Professor Joseph Zarka from Ecole Polytechnique of France. The general approach developed through this project has been used to integrate diverse experimental, theoretical, and computational information, and it has the potential of being developed into a tool with significant practical applications.

50 HSLA-80 steel samples have been transferred to CEAM, and we are going to apply our approach to investigate the fatigue damage of these specimens. We plan to learn more about the details of the fatigue experiments on large-scale beams at Lehigh University so we can improve the accuracy of the predictions. Mr. Jun Huang (graduate student) traveled to Ecole Polytechnique in November 2000, and the procedure to perform 3D numerical analysis has been developed there, and applied here at UCSD. We also plan to introduce a new method of computing equivalent loading history through evaluating accumulative plastic strains. This new approach was developed by Professor Zarka in 2000, and has been refined last year.
IV. SCIENTIFIC AND TECHNICAL PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD

Scientific and Technical Personnel:

Masoud Beizaie (Staff Research Associate): research focusing on the reliability of weldments, especially those used in marine structures. This activity includes extensive literature survey and search for available databases and software.

Joseph Zarka (Visiting Research Scientist from Ecole Polytechnique, France): the research project includes collaboration with Dr. Zarka, who spends at least three months each research year at CEAM of UCSD. The approach, to study the reliability of ship structures and particularly their welded parts, utilizing the automatic Learning Expert System (L.E.S), has been developed by Dr. Zarka.

Graduate Research Assistants:

Jun Huang (9/96 - present): research focusing on fatigue and Dr. Zarka’s new approach to inelastic analysis and the use of numerical analysis software. The research on fatigue includes examination of micro-mechanisms of fatigue, the influence of non-zero mean stress, the accumulative damage theories and the use of statistics in fatigue. The main idea of the new approach is to solve the plastic problem using elasticity solutions. Extensive comparative analysis has been done utilizing the basic components of NISA.

Degrees Attained: None at this time. It is anticipated that Jun Huang will receive his Ph.D. Spring 2003.

V. ONR Database statistics for reporting period (July 1, 01-Feb.02)
Number of Papers Published in Refereed Journals Citing ONR Support: 0
Number of Papers in Press in Refereed Journals Citing ONR Support: 0
Number of Books or Chapters Published Citing ONR Support: 2
Number of Books or Chapters in Press Citing ONR Support: 0
Number of Technical Reports & Non-Refereed Papers: 7
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VI. Journal Publications Appearing in Print (for reporting period July 1, 01-Feb.02)


VII Non-Refereed Publications and Published Technical Reports (for reporting period July 1, 01-Feb.02)


VIII. Books (and sections thereof) Published: None

IX. Presentations (for reporting period July 1, 01-Feb.02)

a. Invited:


b. Contributed:


X. Other Sponsored Science and Technology July 1, 01-Feb.02

"Damage Tolerant Lightweight Armor Materials," ARO DAHR-04-96-1-0376; $1,500,000; 8/15/96 - 8/02.

"Computational Modeling of Strain Localization in Frictional Granular Materials," NSF Grant CMS-9729053; $247,741; 1/1/99-12/31/03.
"Defense University Research Instrumentation Program to Develop Special CCD Camera for Full-Field Time-resolved Data Acquisition for High-Rate Deformation," ARO DAAD19-99-1-0079, Total awarded $219,255 for period 3/31/99 - 3/31/01 (includes 12 month NCE).

"Experimental and Microstructural Characterization, and Physically-Based Micromechanical Modeling of Ionic Polymer Metal Composite," Naval Research Laboratory Grant No. MDA972-00-1-0004, Total Awarded $692,000 for period 3/6/00-3/5/03, Y1: 201,340, Y2: 280,600, Y3: 210,060.

"Special X-Ray Camera Facility for Full-Field Time-Resolved Data Acquisition for High-Rate Deformation," ARO AMXRO-ICA DURIP DAAD19-00-1-0059, Defense University Research Instrumentation: Total Amount Funded $106,163 for period 3/31/00-3/30/02 (includes 12 month NCE).

"Multiscale Multifunctional Materials," ARO/DARPA DAAD19-00-1-0525, Total amount awarded $2,535,427.00 for period 4/01/00-3/31/04.9/1/00 Period A: 2 months $50,000, Period 1: 12 months $451,816, Period 2: 12 months $495,865, Period 3: 10 months $510,139, Period 4 (sub option): 12 months $502,607.

"Fatigue Failure of Hybrid Polymer Composite-Metal Joints," ONR N00014-02-1-0420: Total Amount Awarded $94,379.00 for period March 08, 2002 - March 97, 2003. 1st Increment: $67,000.


XI. COMPLETE LIST OF PUBLICATIONS AND PRESENTATIONS
(April 1996 - June 2002)

Books: Published:


Journal Publications Appearing in Print:
Non-Refereed Publications and Published Technical Reports:


Presentations
a. Invited:

b. Contributed:


