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LIFE PREDICTION COOPERATIVE

NASA Grant #NAG3-1768

Validation of Framework Code Approach to a Life Prediction System for Fiber Reinforced Composites

Final Report

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1. Summary

The grant was conducted by the MMC Life Prediction Cooperative, an industry/government collaborative team, Ohio Aerospace Institute (OAI) acted as the prime contractor on behalf of the Cooperative for this grant effort. See Figure 1 for the organization and responsibilities of team members.

The technical effort was conducted during the period August 7, 1995 to June 30, 1996 in cooperation with Erwin Zaretsky, the LeRC Program Monitor. Phil Gravett of Pratt & Whitney was the principal technical investigator. Table 1 documents all meeting-related coordination memos during this period.

The effort under this grant was closely coordinated with an existing USAF sponsored program focused on putting into practice a life prediction system for turbine engine components made of metal matrix composites (MMC).

The overall architecture of the MMC life prediction system was defined in the USAF sponsored program (prior to this grant). The efforts of this grant were focussed on implementing and tailoring of the life prediction system, the framework code within it and the damage modules within it to meet the specific requirements of the Cooperative. The tailoring of the life prediction system provides the basis for pervasive and continued use of this capability by the industry/government cooperative.

The outputs of this grant are:

1. Definition of the framework code to analysis modules interfaces,
2. Definition of the interface between the materials database and the finite element model, and
3. Definition of the integration of the framework code into an FEM design tool.

2. Statement of Work

Validation of a Framework Code Approach to a Life Prediction System for Fiber Reinforced Composites:

The engine companies and UTSA are participating in a cooperative effort to develop the necessary analytical tools to predict the durability of Titanium Matrix Composites. The cooperative is using a Framework code approach to satisfy the durability prediction code requirements. Development of the framework code, and the technical methods within this code, are being funded by USAF PRDA IV contract #F33615-94-C-2411. Implementation and tailoring of the code to meet the specific requirements of the companies existing design life prediction systems is beyond the scope of the PRDA IV contract. The current proposal is intended to facilitate the additional activities (engineering study efforts, coordination meetings and definition of code interfaces) required to put in place the overall framework code and design life prediction system approach.

This proposal allows for tailoring of the framework code and Ti-MMC database to meet the individual needs of the cooperative members. Also, this proposal allows for the additional coordination activities required beyond the effort funded in the PRDA IV contract. This shall include, but is not limited to, expenses related to attending coordination meetings in Dayton, Cleveland, and/or San Antonio.

3.0 Technical Discussion

3.1 Background

The grant was conducted by the MMC Life Prediction Cooperative, an industry/government collaborative team, composed of the five major domestic gas turbine engine companies and the two federal R&D laboratories located in the State of Ohio. Those contributing organizations are:

AlliedSignal Engines
Pratt & Whitney
Allison Engine Company
GE Aircraft Engines
Williams International
USAF Wright Laboratory
NASA Lewis Research Center

OAI acted as the prime contractor on behalf of the Cooperative. The University of Dayton Research Institute also conducted technical efforts in support of this overall effort under the direction of USAF.

Complimentary efforts were also conducted by the materials and structures researchers at LeRC under the NASA HiTEMP program.

The overall technical effort for the grant was lead by Phil Gravett of Pratt & Whitney and the technical team supporting him is identified in Figure 1. The team was previously organized based on the tasks defined for the already existing USAF sponsored contract entitled "Advanced MMC Life Prediction Methodologies", F33615-94-C-2411.

3.1.1 Related USAF Contract

The effort under this grant was closely coordinated with the existing USAF contract, F33615-94-C-2411, that was initiated prior to this grant, continues beyond this grant, and will be concluded in the first quarter of CY 1998.

The work under the USAF contract identified the overall concept of the life prediction system; a framework code approach with coupled damage modules; Figure 3.

The USAF contract was focused on detailed development and coding of analytical/empirical models for three of the major failure modes (creep, fatigue, and crack growth) observed in these turbine engine composite components.

The efforts by the team participants was defined as follows:

Allied-Signal Engines lead the database effort to establish and consolidate a material database to support the analysis module effort. The database was intended as a source of experimental data validated for use in developing life prediction models.

Pratt and Whitney lead the framework development effort which integrated a FEM structural analysis code with damage modules, developed a primary framework code and standardized the module interfaces.

Allison lead the development of the creep analysis module that also provides evaluations of residual strength and rupture life.

Pratt & Whitney also lead the fatigue crack growth effort which was focussed on predicting the growth of fiber bridged dominant cracks which are expected to occur in gas turbine components.

Finally, GE Aircraft Engines lead the effort to develop a module which would predict life of MMC components subjected to thermo-mechanical fatigue cycling.

3.1.2 Problem Statement

The state of the art for life prediction of MMC turbine engine components was a collection of empirically base models and mechanistic models that did not address the specific component design issues like creep, fatigue and crack growth that exists in gas turbine components. The turbine engine components of interest are those in the "cold section" of the engine, such as, the high and low pressure compressors. Specifically, the rotor stages, blades and frames in the compressor section of the engine.

3.2 Overall Program Approach

The overall approach that was already initiated under the parallel USAF contract was to incorporate these damage modes into complex mission cycles where component stresses and temperatures could be varied with time and mission profile. This approach first characterized these damage modes and corresponding mechanisms for damage accumulation and then with that knowledge refines existing models that form a basis for calculating component cyclic life.

Therefore, under the USAF contract the overall system architecture was defined and a preliminary approach to the framework code was identified.

Under this grant the interfaces with the modules were defined in detail and finalized, the complete functionality of the framework code was established and the user interfaces were defined in detail.

Under the parallel USAF, a software development plan, a user manual and a programmer manual are being provided. A table of contents for each of the documents is provided as Attachment A. As such, the outputs of this grant were integrated into this document, and the reader is encouraged to seek the detail documentation provided in these plans/manuals.

Module interfaces were defined such that modules developed under the Cooperative effort or independently could be coupled with the life prediction system. Therefore, a loosely couple approach was taken for the major interfaces.

3.2.1 Applicable Material Systems

The system architecture developed in this effort was focused on metal matrix composites and is envisioned to be adaptable to organic matrix composites and ceramic matrix composites. This life prediction system would have to be tailored to the damage modes that are prevalent to those composite material systems.

The damage modules developed to support this life prediction system were specifically developed for SCS-6/Ti-6-4 as is currently being processed for turbine engines typically demonstrated under the IHPTET Initiative in the USAF ATEGG and JTDE programs.

3.3 Programmatic Approach

The overall effort was conducted via a series of team meetings, teleconference meetings and coordination memos. A coordination memo system was maintained by OAI on behalf of the team which documents the details of meeting discussions and decisions; identifies detailed interim progress reporting, and assumptions and approaches investigated by the team in the course of the grant.

Table 1. Meeting/Telecon Coordination Memos

Date	Memo No.	Subject
8/7/95	OA-PRDA-95-037	PDG Telecon 8/10/95
8/10/95	OA-PRDA-95-039	MMC Tech Team Telecon 8/8/95
9/19/95	OA-PRDA-95-043	PDG 9/21-22 Meeting Agenda
9/12/95	OA-PRDA-95-047	Tech Team Meeting Agenda
9/26/95	OA-PRDA-95-049	MMC 9/20-22 Meeting Presentations
10/5/95	OA-PRDA-95-050	MMC PDG Meeting & Telecon
10/6/95	OA-PRDA-95-052b	MMC PDG Telecon
11/15/95	OA-PRDA-95-054	10/23 PDG Meeting Minutes
11/15/95	OA-PRDA-95-059	Tech Team Meeting Minutes
11/21/95	OA-PRDA-95-062	11/15 PDG Telecon Minutes
12/13/95	OA-PRDA-95-070	12/11 Minutes - NASA HQ Meeting
1/30/96	OA-PRDA-95-080	1/22 PDG Meeting Minutes
3/5/96	OA-PRDA-95-085	5/18 PDG Meeting Agenda
4/5/96	OA-PRDA-95-086	PDG Meeting Minutes 3/18/96
1/5/96	OA-PRDA-96-006	6/3-4 Tech Team Minutes

The University of Texas San Antonio was initially a contributing member of this collaborative team and was focussed on organizing the materials database. Their effort was terminated prematurely, however, the efforts required by grant were successfully brought to completion under efforts lead by AlliedSignal.

Under the USAF contract, F-2411, quarterly progress reports were released which have included an interim progress status discussion of the efforts conducted under this LeRC grant. As noted earlier, the USAF contract will provide a detailed Programmers and User Manuals for the MMC life prediction system. As such, those efforts are not repeated herein.

3.4 User/System Hardware/Software Requirements

To facilitate the use of these codes as a design/analysis tool, the framework code was designed to run as an FEM structural analysis results post processor. Patran was chosen as the FEM post processing platform because of its availability to all the participants, and will be used to display life results from the framework code. To accommodate the capabilities of all the participants, and to align with existing life prediction codes, the framework code and analysis modules are written in Fortran 77. Although not written exclusively for the Unix operating systems, this was chosen as the preferred computing hardware to integrate the codes into the design/analysis process at the engine companies.

This life prediction system is intended to be used by an experienced designer/analyst familiar with the behavior of MMC material, and as such the programmer and user manuals being prepared under the USAF sponsored program are being written at that information level. This grant final report will summarize the overall efforts and encourages the reader to seek details as reported in the quarterly report and manuals released under the USAF contract.

3.5 System Architecture

Under the USAF Contract, the overall prediction system requirements were defined, as was the preliminary methodology to integrate an available FEM code with the damage modules. A preliminary definition of the framework code structure was also initiated under the USAF contract. This provided a starting point for the LeRC grant.

The approach taken is outlined in Table 2.

Table 2. Approach to Life Prediction System

	LeRC Grant	USAF Contract
• Define prediction system requirements.		✓
• Define a methodology to integrate an available FEM code with damage modules.		✓
• Define preliminary life system framework code structure.	✓	✓
• Establish/document standards for interfaces (framework, database, damage modules, FEM)	✓	✓
• Develop preliminary life system framework code.	✓	✓
• Install damage modules into life system framework code.		✓
• Document code operation and use.		✓
• Concurrent development of individual damage modules.	✓	✓

A modular life system approach was taken as identified in Figure 2.

The framework code integrates the damage evolution modules. A Finite Element Code is not part of the framework code but an interface is defined such that a specified FEM code can be linked for providing stress/temperature histories and viewing results. The framework code and damage module interfaces were defined in detail under this grant, including a) standardization of the interfaces between the damage modules and framework code, and b) the interfaces with the materials database. These were documented under a USAF contract coordination memo. The actual software coding of the framework code and the interfaces, the installation of the damage modules into the life system framework code and the documentation of the code operation and use were accomplished under the USAF contract.

3.5.1 Framework Code

The framework code has several major functional areas that include pre-processing, input deck generator, module interfaces, and life results post processing.

The framework code is a life processor which is integral with a FED post processing code, such as PATRAN. The framework code creates a "framework code" input file, reads material properties from a material library, and reads stresses from FEM results files. Figure 4 illustrates the example input/FEM files. In addition, the framework code can be run stand-alone from a prompting interface. See Figure 5.

The input deck generator takes the input info read or accessed in the preprocessor and creates the required input deck format for each life analysis module. The input deck generator assembles the analysis parameters and materials properties at the beginning of the input deck, then assembles the stress/strain history for each analysis point sequentially, as illustrated in Figure 6.

The module interfaces are defined such that the analysis modules are called as stand alone programs, rather than subroutines of the framework code. The modules are called as arguments which define the input and output files, Figure 7, for the module interface statements. Each analysis routine is completely computationally isolated from the rest of the codes, except for the reading of the input deck and writing of an output file. This is key to independent development of analysis routines.

The post processor creates a life results file which then can be displayed on the finite element mesh.

3.5.2 Damage Modules

The damage modules that were focused on for this effort accounted for creep/rupture, thermal-mechanical fatigue and crack growth.

The creep module, a micromechanics based model, integrated with a constitutive model, can synthesize component behavior throughout the full mission cycle and post-process the stress and deformation results to obtain residual strength and life of the component.

The rupture model has been defined to read FEM results directly from PATRAN format files and output back to the PATRAN database so the results can be reviewed graphically. The rupture model has been based on the reduction of the cross-sectional area.

The crack growth module is based on empirically calibrated crack growth models and was being developed to predict the growth of fiber bridged dominant cracks which are expected to occur in the turbine engine components. This includes surface flaw and corner crack geometries.

The thermal-mechanical fatigue module is based on the GE fatigue code NASALIFE model. This code has various multiaxial and mean stress models and is being used to determine the fatigue capability of the matrix and fiber under thermomechanical loading.

3.5.3 Material Test Data Format

The materials data files were placed in an MVision database configuration. The actual materials data were collected from the engine companies, WPAFB, and LeRC under a task in the USAF contract.

The materials database files were initially configured in an EXCEL database and then electronically transferred into an MVision database configuration.

3.6 User and Programmer Manuals

The User and Programmer Manual being provided under the USAF contract will consist of two main sections, one to describe the technical content and verification of the modules, and the second to describe code operation with input and output descriptions. The first section of the manual will primarily consist of the detailed descriptions of the analytical solutions incorporated into each module. This will include the formulation and derivation of the solutions with supporting data for verification. Also, procedures for selecting stresses and temperatures from a flight profile will be defined. As assessment of the accuracy of each module will also be stated. The second section will consist of all the information required for a user to complete an accurate life prediction for each module and all options available for each module. This will include operating instructions, input and output descriptions, input and output examples, and list of typical input errors encountered by users.

The Table of Contents for the User and Programmer Manual is provided in Attachment A.

3.7 Points of Contact

The following is a list of points of contact for the various subareas of this MMC life prediction system:

Topic	Contact	Phone/E-Mail
LeRC Grant Monitor	Erwin Zaretsky	216/433-3241/216-433-5802
USAF Contract Monitor	Capt. Dana Allen	937-255-2734/937-255-2660
Principle Technical Investigator	Phil Gravett	561-796-5978/561-796-8993
Grant Program Manager	Wally Rakowski	440-962-3126/440-962-3056
System Architecture and Framework Code	Phil Gravett	561-796-5978/561-796-8993
Materials Database	Howard Merrick	602-231-1884/602-231-1353
Creep Damage Module	Charlie Dantzer	317-230-2521/317-230-6514
Thermomechanical Fatigue Module	Don Slavik	513-243-4499/513-243-4886
Crack Growth Module	Dave Walls	561-796-6547/561-796-8993

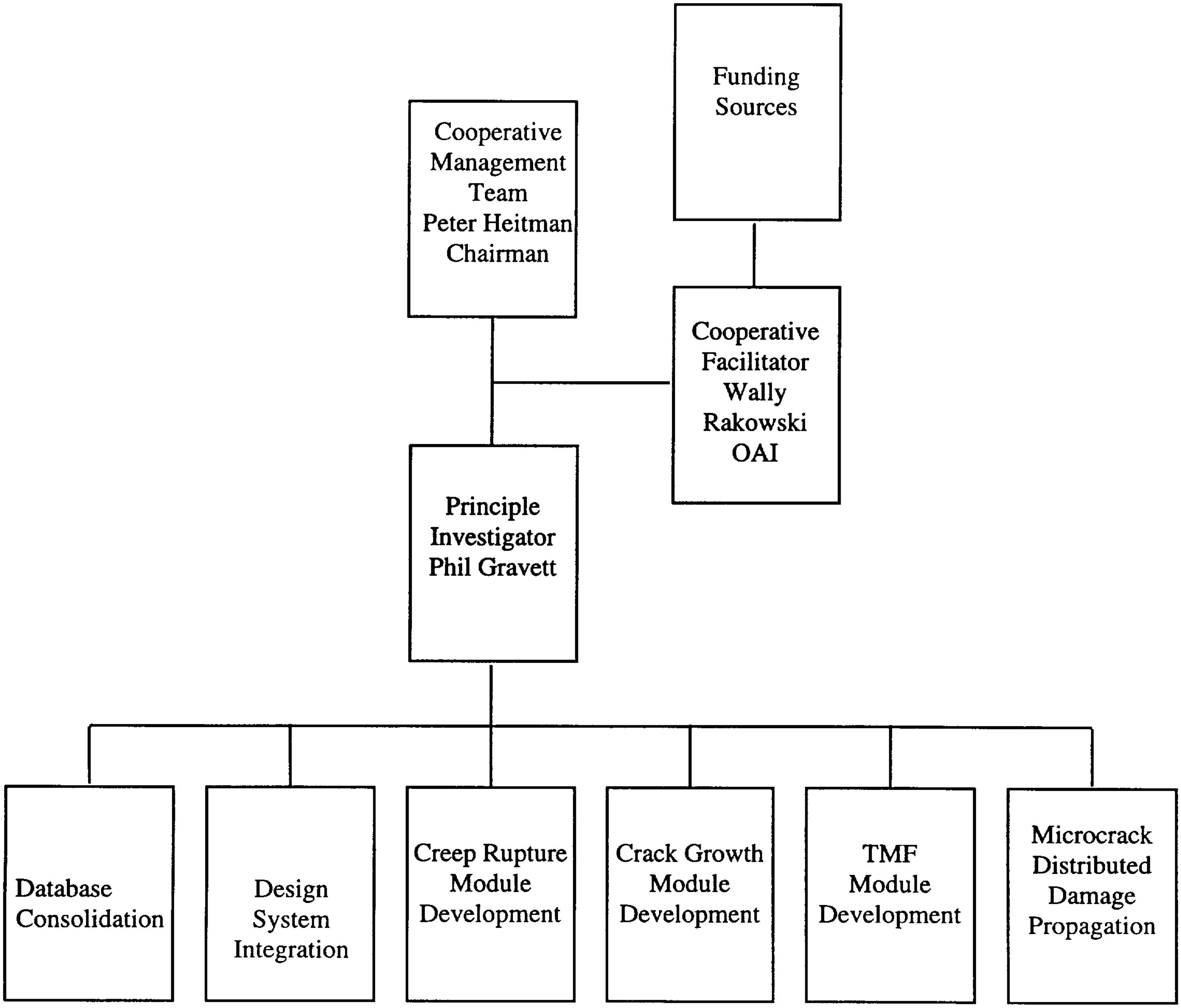


Figure 1. MMC Organization Structure

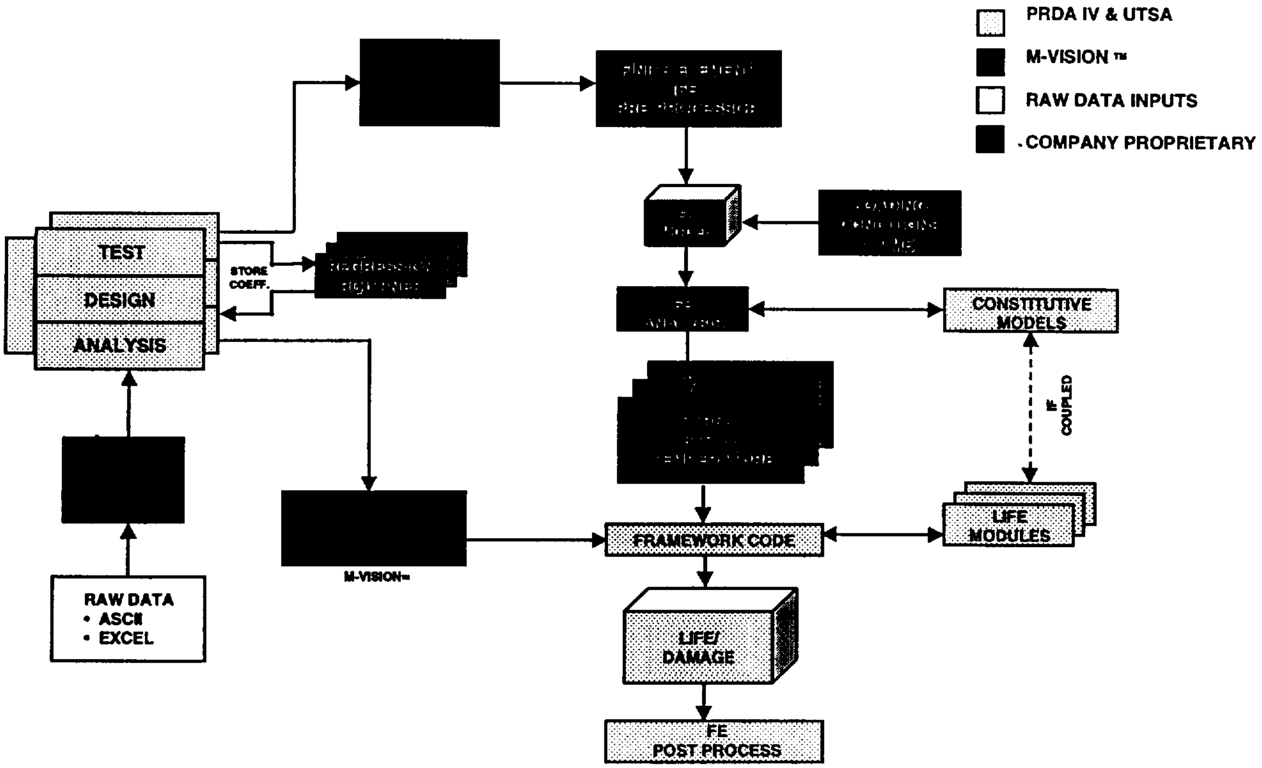


Figure 2. MMC Life Prediction System

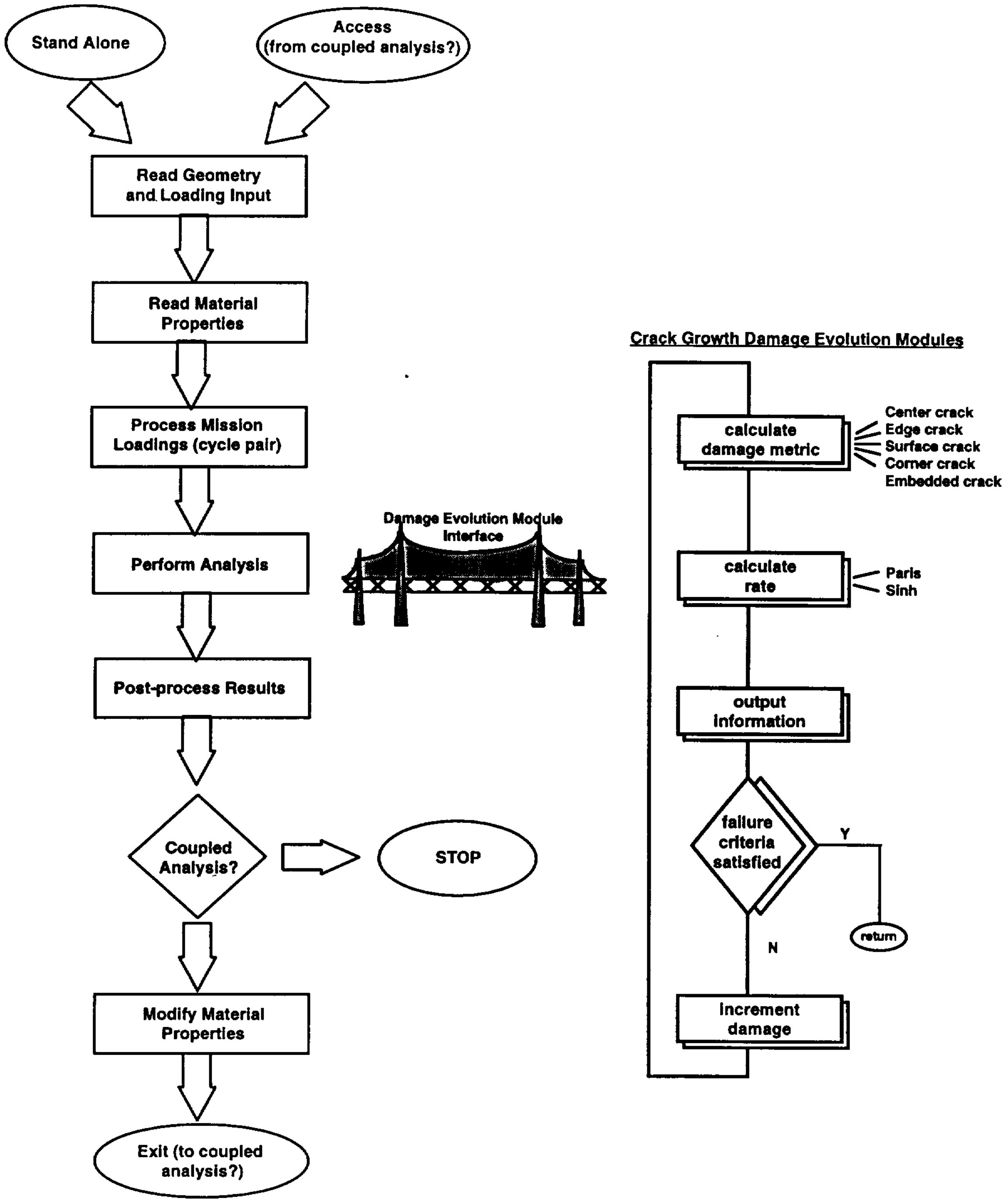
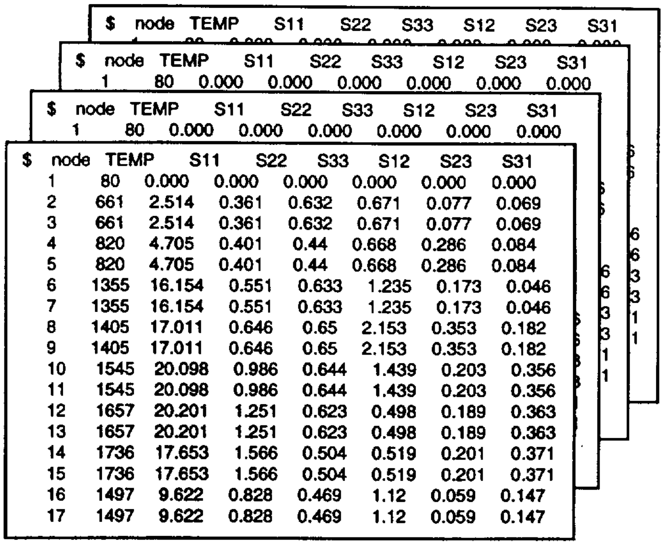


Figure 3. Modular Code Framework

Input File

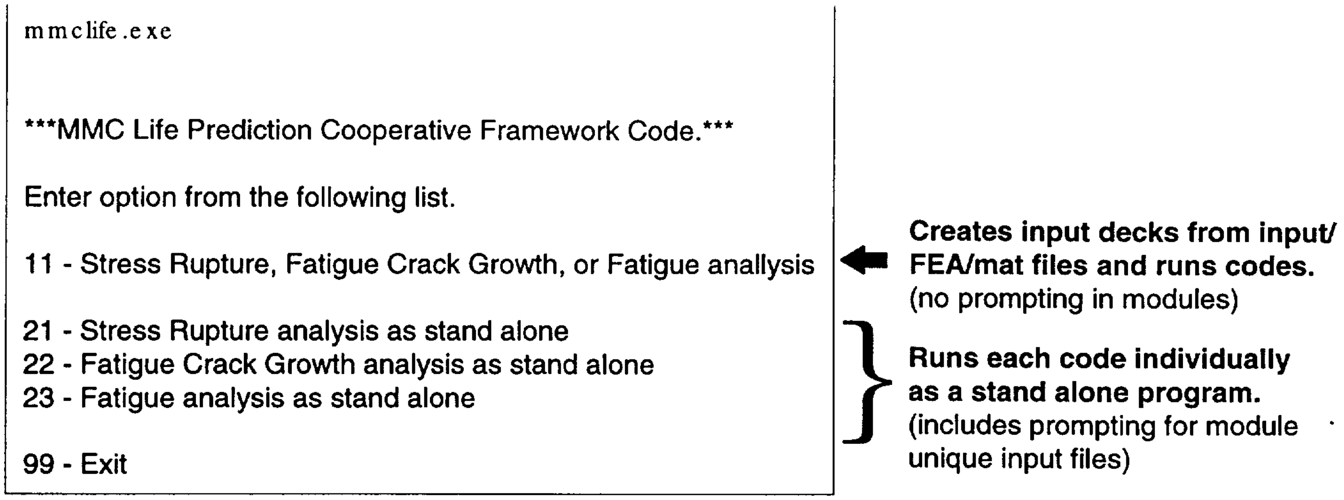
```
$ MMC Life Prediction Cooperative Framework code input deck
$ FCG test case
$ Title
FCG test case
$ material name
test
$ Stress Rupture analysis, input parameters
rupture
$ Fatigue Crack Growth anslysis, input parameters
$ fcg flag, t, w, fib dia, vf, fmtyp, fmlamb, a, a0, aoc, iaoc, crktyp, aoc eq.
fcg 1.0 2.0 .0056 .34 2 1 .020 0.0 1.0 0 13 1.0 0.0 0.0
$ Fatigue anslysis, input parameters
$ fatigue flag
fatigue
$ mission stress/temp history, input/file/fea
mission fea
$timepoint, filename
1. time1.fea
2. time2.fea
3. time3.fea
4. time4.fea
end
```

Current simplistic FEA output File



```
$  node  TEMP    S11     S22     S33     S12     S23     S31
    1     80   0.000   0.000   0.000   0.000   0.000   0.000
    2    661   2.514   0.361   0.632   0.671   0.077   0.069
    3    661   2.514   0.361   0.632   0.671   0.077   0.069
    4    820   4.705   0.401   0.44    0.668   0.286   0.084
    5    820   4.705   0.401   0.44    0.668   0.286   0.084
    6   1355  16.154   0.551   0.633   1.235   0.173   0.046
    7   1355  16.154   0.551   0.633   1.235   0.173   0.046
    8   1405  17.011   0.646   0.65    2.153   0.353   0.182
    9   1405  17.011   0.646   0.65    2.153   0.353   0.182
   10   1545  20.098   0.986   0.644   1.439   0.203   0.356
   11   1545  20.098   0.986   0.644   1.439   0.203   0.356
   12   1657  20.201   1.251   0.623   0.498   0.189   0.363
   13   1657  20.201   1.251   0.623   0.498   0.189   0.363
   14   1736  17.653   1.566   0.504   0.519   0.201   0.371
   15   1736  17.653   1.566   0.504   0.519   0.201   0.371
   16   1497   9.622   0.828   0.469   1.12    0.059   0.147
   17   1497   9.622   0.828   0.469   1.12    0.059   0.147
```

Figure 4. Example Framework Code input and representative FEA results files.



```
mmclife.exe


***MMC Life Prediction Cooperative Framework Code.***

Enter option from the following list.

11 - Stress Rupture, Fatigue Crack Growth, or Fatigue anallysis

21 - Stress Rupture analysis as stand alone
22 - Fatigue Crack Growth analysis as stand alone
23 - Fatigue analysis as stand alone

99 - Exit
```

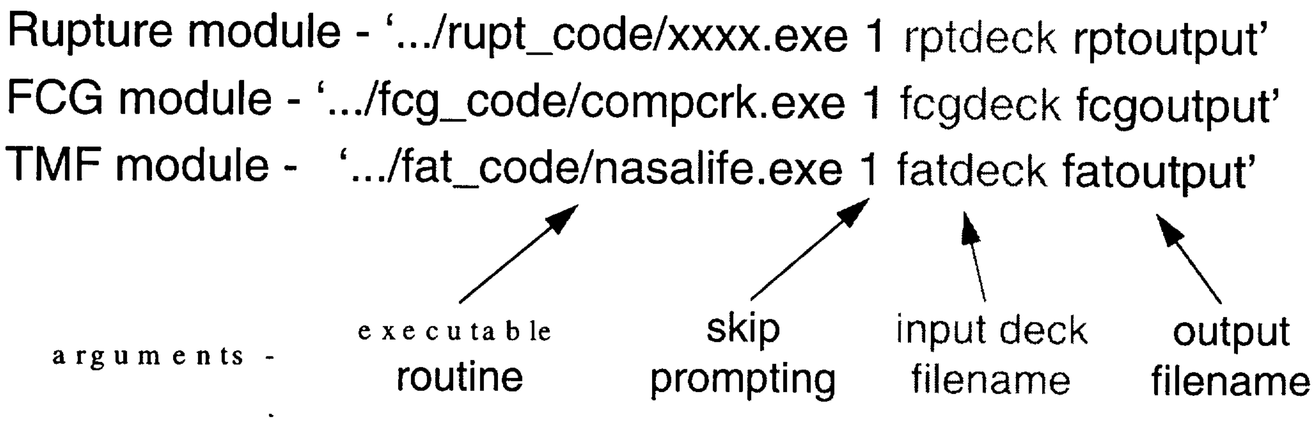
Creates input decks from input/ FEA/mat files and runs codes. (no prompting in modules)

Runs each code individually as a stand alone program. (includes prompting for module unique input files)

Figure 5. Prompting Options for Preliminary Simple Preprocessor.

```
RUPT42
FRUP
  -20.9
PRUP
 0.0109
LCF
TITLE
Max in-plane stress location at supersonic cruise (ksi)
ARATIO
      1
WSAL    FLIF      FLAG    TEMP
 19.5        2       0      70
 18.5       42
 17.5      694
 16.5    11580
.
.
.
WSAL    FLIF      FLAG    TEMP
 12        7         0    2400
 11      314
 10    14723
  9   690558
EOF
MATL
IOP2
TEMP    M         FLAG
  70  -99            0
2400  -99            0
TEMP      E       K       N       V     FLAG
  70    33408    999     0.1   0.083       0
2400    32010    999     0.1   0.169       0
EOF
$ PCG input deck for node    1  (run #    1 )
 TIME TEMP S11 S22 S33 S12 S23 S31
   1.000   80.000    0.000    0.000    0.000    0.000    0.000    0.000
   2.000   80.000    0.000    0.000    0.000    0.000    0.000    0.000
   3.000   40.000    0.000    0.000    0.000    0.000    0.000    0.000
   4.000   60.000    0.000    0.000    0.000    0.000    0.000    0.000
EOF
$ PCG input deck for node    2  (run #    2 )
 TIME TEMP S11 S22 S33 S12 S23 S31
   1.000   80.000    0.000    0.000    0.000    0.000    0.000    0.000
   2.000  661.000    2.514    0.361    0.632    0.671    0.077    0.069
   3.000  330.000    1.257    0.180    0.316    0.336    0.038    0.035
   4.000  495.000    1.885    0.270    0.474    0.504    0.057    0.053
EOF
.
.
.
.
```

Figure 6. Example TMF Module input deck.



```
Rupture module - '.../rupt_code/xxxx.exe 1 rptdeck rptoutput'
FCG module - '.../fcg_code/compcrk.exe 1 fcgdeck fcgoutput'
TMF module -   '.../fat_code/nasalife.exe 1 fatdeck fatoutput'
```

Figure 7. Modules call statements with arguments defining options and input/output files.

Attachment A

MMC Life Prediction Cooperative

Final Report

LIFE PREDICTION COOPERATIVE

Contract #F33615-94-C-2411

Advanced MMC Design/Life Methodologies

Software Development Plan
CDRL Data Item A011

Prepared for:
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         - Example Output
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