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The Effect of Loading Parameters on Fatigue of Composite Laminates: Part IV Information Systems

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16. Abstract

Damage tolerance, damage resistance and durability assessments of aircraft composite structures are essential components of certification. The certification procedure requires lengthy experimental validation of those assessments, although much research has been conducted to understand the behavior of polymer matrix composites under service conditions. A fair amount of data is available together with a number of analytical models in these areas of research. However, because of the vast number of parameters involved, a generic model is rather difficult to develop. The ultimate goal of this study is the identification of design parameters to be used in the development of information system tools that can help engineers synthesize different sets of data efficiently.

In the information system developed in the current work for structural behavior with damage, all parameters that have been studied are available for the user to choose as input. The output contains design parameters such as compression strength after impact, dent depth, and damage area as well as literature references, raw data, tables, and plots. The information system is constituted in a relational database environment and tools from expert system technology are incorporated so that low confidence input can be captured and flexibility can be maintained in similarity assessments. With this system it is also possible to conduct parametric studies to determine the effect of each design parameter or a combination of parameters on the damage behavior. Case examples are included to demonstrate practical uses of the information system for both data retrieval and similarity studies.

A similar system was developed for fatigue design of composites. Design parameters were identified as well as the values these parameters can take. Results of the parameter identification study have been used to create a conceptual data model. Again, interfaces were developed to provide the design engineer with practical tools for data synthesis. Case examples are included to demonstrate the use of the interfaces.

In both systems, all experimental data generated under the current grant has been stored along with data collected through a literature survey. The systems are used for data synthesis which extends the composites fatigue design and damage behavior knowledge bases. Such knowledge bases are instrumental in the determination of design recommendations which is the ultimate goal of the research project.

Copies of these two informational databases, Damtol and Durability can be downloaded from the FAA FTP site: The address for the Damtol database is http://aar400.tc.faa.gov/database/Damtol.mdb. The address for the Durability database is http://aar400.tc.faa.gov/database/Durability.mdb.

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LIST OF ACRONYMS

BVID	Barely Visible Impact Damage
C.A.	Constant amplitude fatigue loading
C-C	Compression-Compression fatigue loading
T-C	Tension-Compression fatigue loading
T-T	Tension-Tension fatigue loading
CSAI	Compressive Strength After Impact
RCS	Residual Compressive Strength (after postimpact fatigue)
UTS	Ultimate Tensile Strength
UCS	Ultimate Compression Strength
TWIST	Transport WIng Standard Test Spectrum
DUL	Design Ultimate Load
AI	Artificial Intelligence
DSS	Decision Support Systems
DBMS	Database Management System
LSS	Laminate Stacking Sequence
NDE	Nondestructive Evaluation
NTS	Notched Tensile Strength
NCS	Notched Compression Strength
SQL	Structured Query Language

EXECUTIVE SUMMARY

This report is the fourth in a continuing series of reports that will provide a comprehensive study of the damage induced by spectrum fatigue loading in composite laminates and its influence on residual mechanical properties. The overall study will delineate the effects of component parts of the load spectrum on fatigue damage development and provide recommendations for fatigue design of composite laminates and accelerated testing methodology. This report focuses on the development of an information system to organize and retrieve damage tolerance and durability data.

Damage tolerance, damage resistance, and durability assessments of aircraft composite structures are essential components of certification. The certification procedure, requires lengthy experimental validation of those assessments. A fair amount of data is available together with a number of analytical models for composite materials. However, because of the vast number of parameters involved, an all encompassing generic model is rather difficult to develop. The main objective of this study is the identification of design parameters to be used in the development of information system tools that can help engineers synthesize different sets of data efficiently.

In the information system for structural behavior with damage, all parameters that have been studied are available to the user to choose as input. The output contains design parameters such as compression strength after impact, dent depth, and damage area as well as literature references, raw data, tables, and plots. The information system is constituted in a relational database environment and tools from expert system technology are incorporated so that low confidence input can be captured and flexibility can be maintained in similarity assessments. With this system it is also possible to conduct parametric studies to determine the effect of each design parameter or a combination of parameters on the damage behavior. Case examples are included to demonstrate practical uses of the information system for both data retrieval and similarity studies.

A similar system was developed for fatigue design of composites. Design parameters were identified as well as the values these parameters can take. Results of the parameter identification study were used to create a conceptual data model. Again, interfaces were developed to provide the design engineer with practical tools for data synthesis. Case examples are included to demonstrate the use of these interfaces.

In both systems, all experimental data generated under the current grant has been stored along with data collected through a literature survey. The systems are used for data synthesis which extends the composites fatigue design and damage behavior knowledge bases. Such knowledge bases are instrumental in the determination of design recommendations which is the ultimate goal of the research project.

1. INTRODUCTION.

One of the obstacles to wider application of composites in aircraft structures is the difficulty in certifying composite structures. Being fairly new, composites do not yet enjoy the kind of databases that conventional materials do. Thus, certification requires extensive testing of elements and components under realistic loading environments. It therefore makes economic sense to modify the loading spectrum to reduce testing time as much as possible.

The main goal of the present study is to delineate the effects of various parameters defining spectrum loading on damage growth. Once these effects are identified, one can accelerate durability testing by changing appropriate loading parameters. The first three reports [1,2,3] addressed the effects of preload, block loading, stress ratio, and loading frequency on damage development in plain coupons and specimens with a stress raiser in the form of centrally located hole as well as the influence of these loading parameters on impact-induced delamination growth in composite laminates containing barely visible impact damage. This report addresses the development of information systems that store and retrieve relevant experimental data for behavior of composites with damage in fatigue.

Composites are materials of choice for light-weight structures due to their excellent weight/strength and weight/stiffness properties. In aerospace applications, composite panels may be subjected to low-velocity impacts under long-term mechanical loading. The resulting damage grows in the form of matrix cracking, delamination and fiber breakage causing degradation in mechanical properties, especially in compression. Both damage tolerance and long-term behavior of composites were studied extensively over the years, resulting in a fair amount of data complemented by a number of analytical models. However, a generic methodology to design for fatigue of composites is difficult to develop because of the vast number of parameters involved. The present study offers a solution to this problem by creating a common environment where data from different materials, loading conditions, and structures are brought together for synthesis.

Durability and damage tolerance may have different connotations to people from different industries and with different backgrounds. Damage tolerance always refers to a safety of flight issue where the structure must be able to sustain design limit loads in the presence of damage and land safely. Durability, on the other hand, is an economic issue where the structure must be able to survive a certain life under load before the initiation of observable damage. In the present study, impact damage and fatigue behavior of composite structures are described and design parameters are identified and categorized in preparation for the development of pertinent database structures for composites.

Understanding the influence of impact damage on the residual mechanical properties is especially important for composites. Barely visible low-velocity impact damage can significantly reduce the compressive strength. Low-velocity impacts can occur during manufacturing, maintenance, and service of composite structures. Common examples of damage sources in aerospace applications are tool drops during maintenance, hail, and runway debris. The basic concepts of damage development during impact and its influence on residual mechanical properties are discussed along with a survey of the work in the literature pertinent to damage tolerance and damage resistance of composites. The role of damage tolerance and resistance in civilian aircraft certification is also discussed. Finally, impact damage tolerance parameters are identified and grouped in preparation for the development of a database structure.

Computer-based information systems have rapidly emerged in all areas of industrial and personal applications. The engineering community has long been familiar with knowledge work systems that promote the creation of new knowledge and its integration among different elements of a project. Computer Aided Design (CAD) and commercial Finite Element Model (FEM) packages are well-known examples. These knowledge-level systems had been the fastest growing applications in the former part of the last decade. In recent years, Decision Support Systems (DSS) have been increasingly developed and implemented to complement knowledge-level systems. DSS help engineers to make decisions that are semistructured, unique or rapidly changing. It is necessary for fast decision making that the problem of selection be reduced to its main elements through the screening of attributes ill suited to the given requirements. This process of screening assists the decision-maker by reducing the number of viable alternatives that would then undergo analysis and experimentation. This type of a software system would especially be applicable to damage and durability behavior of composites where design parameters and alternatives for those parameters are numerous. Such a system can be created under a well-structured database environment. On the other hand, another branch of information systems, called expert systems, deals with accommodating uncertainty and low confidence information as well as suggesting recommendations as output when applied to a specific problem. Such methods have proven useful to capture the heuristic approach of an expert in solving specific and complex problems. Consequently, a comprehensive tool with database and expert system characteristics is apt for composites durability and damage behavior due to the nature of these problems. These two technologies of information systems are discussed and compared including examples of their applications in composites science and engineering. Their similarities and complimentary properties are studied to help develop a hybrid information system. Also a weighted average reasoning mechanism is presented that evaluates incomplete durability and damage tolerance information.

A study was conducted on information systems aimed at combining the two tools of information processing by employing some of the expert system development techniques to a relational database structure. Besides offering standard database functions, the information system called *DamTol* also has a module, called Expert Solution, that determine similarity between the specified input parameter values and cases that are stored in its database. The capability of this module has been expanded to handle low confidence inputs.

In a similar fashion to damage behavior information system, a comprehensive software tool called *Durability* has been developed for the fatigue behavior of composite structures. A conceptual data model was developed to form a relational database structure by using the design parameters that have been identified through the literature survey. Durability also has the data entry and querying and similarity study user interfaces.

2. BACKGROUND.

In aircraft applications composite panels are routinely subjected to both low-velocity impacts and long-term mechanical loading (fatigue). These loading events cause damage to develop in the form of fiber breakage, matrix microcracking, and delaminations which lead to material property degradation with the most severe being compression strength. This reduction raises serious concerns about using composite components in the critical locations of an aircraft which must support nominal compressive loads during normal operation, and it represents one of the major issues for satisfying the safety requirements of the aircraft structures. An overview of the work done by other researchers aimed at characterizing and predicting damage growth in composite materials during various loading scenarios is presented in the following sections. Parameters that affect damage initiation and accumulation during impact and fatigue loading are examined, together with the influence of various damage states on the residual mechanical properties and strength.

2.1 IMPACT DAMAGE IN COMPOSITES.

Certification of civil aircraft composite structures requires practices that are unique to these material systems. One of the requirements of certification is the proof of damage tolerance and the establishment of the extent of damage for residual strength assessments [4]. Being of more recent origin, the design and service experience of composites is substantially less than that of conventional materials. Thus, more testing is required to provide data for static, fatigue, and damage tolerance proof of the structure. Analysis can only be used if similarity is shown to other structures proven by experimentation as well as analysis.

Impact damage evaluation of the structure is an integral part of the certification program that requires lengthy experimental efforts under realistic loading environments. Therefore, designers seek to find similarities between new and in-use designs to reduce their impact damage tolerance certification test matrix. Composite material damage tolerance testing programs and subsequent validation of the structure are too dependent on expensive testing and a need has been expressed for a better design tool that would save costs by using analytical extrapolation within a more limited test matrix [5].

Parameters affecting residual strength after impact are numerous which inhibit simple comparison techniques [6]. A database structure is needed to make better use of the available data. To address similarity and applicability between designs, the data need to be effectively retrieved and utilized. Two design issues for composite materials are damage resistance and impact damage tolerance. The former is the extent of damage, which is measured by dent depth and/or damage dimensions such as area and diameter, and the latter is the performance of the structure after impact which is measured by the residual mechanical properties such as strength after impact, ultimate strain after impact, and residual stiffness. Both issues are of equal importance and play interdependent roles in design. For example in the range of barely visible impact damage (BVID), one certification requirement is the proof of sustaining design ultimate loads (DUL). Hence, an impact damage database should contain information pertinent to both of these considerations.

2.2 FATIGUE DESIGN OF COMPOSITES.

Performance specifications for current and proposed composite structures require that materials maintain certain minimum properties throughout their service life. Hence, durability is mainly an economic consideration since maintenance, repair, or modification costs depend on adequate durability. Composite structures develop damage under long-term loading that might lead to total failure. The damage mechanisms involved are complex and depend on many parameters such as fiber and matrix materials, stacking sequence, geometry, and load levels.

Fatigue behavior of composite materials and structures is a phenomenon consisting of cyclic thermal or mechanical load-induced events and processes over time which determine long-term performance. These events, generically called damage in the composites literature [7], combine in such a way as to change the response of the composite to the extent that it may fail to satisfy its intended service requirements. Fatigue loading of composite laminates consists of the application of loads and strains that reach amplitudes which are less than the values required to fracture the laminates in monotonic loading. Consequently, if failure due to this type of loading occurs, then damage must have developed in the laminate during the fatigue lifetime and caused degradation of properties such as strength and stiffness.

S-N type fatigue curves for composites are relatively flat compared to the curves for metals. An S-N curve is even flatter for spectrum fatigue since peak loads only occur a few times within the spectrum. Hence, it can be deduced that constant amplitude fatigue test results are conservative when compared to typical aircraft flight loads and that only the peak loads have a degrading effect on the material. There have been many experimental studies conducted to determine the fatigue behavior of composites. These studies produced an immense amount of fatigue data. Moreover, each experimental study developed data analysis tools that were used in the specific study with fatigue models specific to the loading conditions, geometry, and material system. There is no software tool today that brings together all the data collected under different design conditions.

2.3 DATABASES AND EXPERT SYSTEMS.

Although databases and expert systems have some similarities, the approach they take is conceptually different. Both technologies can be grouped under the category of information systems. They are developed and used to enhance information processing. Databases store large amounts of facts extensionally. In order to use the database, the user must supply intentional definitions to retrieve the data that is required. An expert system, on the other hand, stores a number of intentional definitions and the user must supply specific information about a particular case to which these definitions can be applied. From this standpoint, it can be seen that the two technologies complement each other. In both approaches general expertise is applied to specific information, but while the database supplies specific data, the expert system is supposed to supply expertise. These definitions also indicate that databases contain large amounts of data, which is available for use in a variety of tasks, whereas expert systems hold only a small amount of data and are problem specific [8]. Therefore in database design, the main concerns are efficient data storage and retrieval while expert systems involve capturing and representing expert knowledge and problem solving reasoning and the ability to handle low confidence inputs.

2.3.1 Expert System Technology Applications in Composites.

An expert system is a computer program that applies human knowledge and reasoning used by the human expert in a specific area of expertise to offer solutions to difficult problems. Since it can not be transferred from one problem domain to the other, expert knowledge is often scarce and valuable. Expert systems are computer programs that capture some of that knowledge and allow its dissemination to others. As problem solving tools, expert systems utilize the research disciple of Artificial Intelligence (AI) to create a commercial reality that produces benefits in diverse applications. As a branch or spin-off of AI, expert systems can use other AI applications as tools, such as fuzzy logic, neural nets, genetic algorithms, and smart agents.

One important fact about an expert system application is that it is only as useful as the knowledge it represents. Its performance greatly depends on the experts, knowledge engineers, and the developers. Properties that define an expert system can be identified as follows. Its reasoning is based on symbolic manipulation rather than numerical manipulation and incorporates judgment into the system. Moreover, an expert system can explain exactly how it reached an answer in a user-understandable format. Finally, depth in the representation of knowledge makes an expert system different from conventional computer programs. From a structural point of view, an expert system's vital parts are its inference engine, knowledge-base, justifier/scheduler, and user-interface.

Several expert system applications have been developed to facilitate the vast amount of information generated and also to retain pertinent knowledge of composites technology. The use of expert systems in composites technology is relatively new compared to other engineering disciplines due to the fact that modeling required for analysis of composite structures is numerically intensive. As the main strength of expert systems comes from enabling symbolic representation, a change in thinking is needed to incorporate them in the product development cycle.

One area of application is the intelligent curing cycle development and control. Ciriscioli, Springer, and Lee built expert system software to simulate, develop, and control parameters for autoclave curing of thermoset matrix composites [9]. Shin, Lia, and Hahn devised a similar system for hot-press curing parameters and extended the expert system capability to feed back forecast information into the on-line curing cycle [10].

Another area of expert system application is in materials and process selection. Since the material characterization, structural design, and manufacturing of composites require different and extended amounts of expertise, a design engineer specializing in one field might not be as familiar with the others. Some expert systems have been developed as aides in pursuit of concurrent engineering. Pitchumani and Karbhari developed DSS Preform, an expert system software, to assist in the manufacture of preforms used in the infiltration processing of ceramic and metal matrix composites [11]. Another good example in this area is the Composites Design and Manufacturing Critiquing System developed by Messimer, et al. that evaluates a design submitted by the user and offers suggestions on process selection [12].

The design of composites has also emerged as a focus of expert system development. Since the complexity of composites design problems calls for expert knowledge, numerous systems have been incorporated for specific problem domains. One example is the expert system for composites design developed by Morton and Webber that facilitates a heuristic redesign method for the stiffness effective design optimization of composite plates under multiple loading cases [13]. Another example, developed by Allen and Bose, is Assistant Composite Laminate Designer (ACOLADE) code, which combines classical lamination analysis with design heuristics [14].

Some studies focus on the knowledge representation and inference strategies of DSS applications for the conceptual design of polymer composite assemblies [15]. Conceptual design DSS are also extended to offer solutions for cost estimation in composites manufacturing by the incorporation of activity based costing models [16]. In the fields of durability and impact damage tolerance design of composites, intelligent systems have not been employed previously, probably due to the scarcity of readily available knowledge and the high volume of data that needs to be processed.

2.3.2 Relational Databases and their Application in Composites.

In a database, information is divided into small units called data and stored within tables that are divided into fields. Due to the use of tables in both databases and in spreadsheets, the objective of using a relational database may not be immediately apparent. The primary objective of databases is to allow for efficient methods of storing and retrieving data, whereas spreadsheets are mainly used for processing data. The key to efficient storage and retrieval of information in databases lies in the ability to create an integrated data structure by defining relationships that are inherent in the information being stored. In other words, a significant amount of information is captured by the data structure and relationships between tables, thus significantly reducing the data redundancy and minimizing data storage requirements. This superiority is the reason why these types of databases are called *relational databases* and spreadsheets are said to have *flat file* structures. It should be noted, however, that relational databases in general and MS Access 97 in particular can also become powerful in processing data by utilizing programming languages like Visual Basic.

Databases are managed by their database management systems (DBMS). The DBMS help create a standard environment in which end users have better access to more and better-managed data. Also, the probability of data inconsistency is greatly reduced in a properly designed database that is managed through DBMS. From these facts, it can be understood that DBMS have two roles. Their first role is to provide a well-structured environment for data storage and their second role is to provide a user-interface for translating user requests into complex code required to fulfill those requests. Database design usually deals with the structuring of the database to store and manage data rather than the design of the DBMS software. Once the database design is completed, the DBMS handle all the complicated activities required to translate the designer's view of data management into structures that are usable to the computer [17].

To create an optimum structure for a database, there are several rules and guidelines asserted by the Normalization Theory. Normalization is defined as a process for assigning attributes to entities to reduce data redundancies and, by extension, helps eliminate the data anomalies that result from those redundancies. The rules of the Normalization Theory are applied in a linear progression to a database, resulting in a more efficient design with each higher normal form.

- First Normal Form: All column values of every table are atomic. The information stored in each column is "indivisible." In other words, information such as a report's author is stored in separate columns of "last name" and "first name," rather than being combined into one column called "name."

- Second Normal Form: First Normal Form conditions apply plus every nonkey column is fully dependent on the primary key. A primary key is a field (column) of a table that uniquely identifies each record (row) of a table. For example, to record information from experiments on a given specimen, the specimen number can serve as the primary key. Any other pertinent information about the specimen such as dimensions or test conditions would be nonkey and fully depend on the primary key.

- Third Normal Form: Second Normal Form conditions apply plus all nonkey columns are mutually independent. One example of dependency is calculated columns. A calculated column in a table has data that can be derived mathematically from one or more other columns of the same table.

Databases are considered as one of the criteria in determining extent of testing and are crucial for addressing similarity between designs and material systems. Whitehead indicates that there has been enough data accumulated in the past three decades and in the light of existing databases, the need for a new certification procedure can be fulfilled [18].

Database structures have been successfully applied in the composites field. Two examples are the Composites Information System (COINS) and the Mechanical Properties of Textile Composites Database; both developed to store data collected under the National Aeronautics and Space Administration (NASA) Advanced Composites Technology (ACT) program. The COINS database contains not only material property data, but also fabrication, service, maintenance, and cost data for all types of composite airframe structures. It aims to provide future airframe preliminary design and fabrication teams with a tool through which production cost can become a deterministic variable in the design optimization process [19]. Mechanical Properties of Textile Composites Database, on the other hand, contains extensive textile composite data. All data in this database come from individual coupon test results because panel, subcomponent, and component level data have been excluded. Manufacturing and testing specific data are also included [20]. Both databases provide NASA customers a single source where data sharing is facilitated. Neither COINS nor the Textile Composites database contain enough data fields for a sufficient study of impact damage and durability behavior of composites. For an effective study, a database structure dedicated to fatigue and impact damage behavior data is necessary.

3. PARAMETER IDENTIFICATION.

3.1 DAMAGE TOLERANCE AND RESISTANCE.

Low-velocity impact damage causes fiber breakage, matrix cracking, and delamination. At the point of contact with the impactor, fibers typically break, substantially reducing the tensile strength of the specimen. However, while low-velocity impact causes a fairly complicated damage pattern, the dominant damage mode for this type of loading is the formation of single or multiple delaminations between the plies of the laminate. The residual strength of impacted composite plates can be reduced significantly, depending on the type and extent of damage. Influence of delamination on the degradation of residual compressive strength has been well documented in the literature. A review of this literature has been reported in reference 3. It has been shown that compressive residual strength values are well below that of a similar structure containing a hole with diameter size equal to the diameter of the impactor. Therefore, compression impact damage is more deleterious than an open hole in composite laminates. The material system and its undamaged properties, the impact event and its conditions, the geometry of the structural application, loading and environmental conditions, and the configuration of the laminate affect the residual properties and the extent of damage induced. The total number of parameters is too many to vary in an experimental study and researchers often fix most of these parameters and vary only one or some to determine their effects.

Although some testing standards have been developed, reported testing conditions still vary widely in the composites literature. Thus, the number of parameters is still too many to make easy comparisons between data sets and designs. This is also an inhibiting factor in developing generic models for impact behavior; hence, such a model is not yet available. Considering reported information and certification requirements, parameters of composites impact behavior have been identified and can be grouped under various categories.

3.1.1 Material System, Laminate Configuration, and Baseline Material Properties.

Material variables include fiber, matrix, and their combined architecture in lamina form. The performance of the composite is influenced by the fiber and matrix architecture and this is characterized by the fiber and resin distribution, interlayer structure, and other micromechanical properties. At the macroscopic level, fiber type, matrix type, and the material system of the combined architecture at lamina level are considered as characterization parameters for damage behavior (table 1). These material systems are distinguished by specific industrial names given by their suppliers.

The manufacturing method also has influence on the lamina properties. Various methods for manufacturing composites exist, including hand lay-up, automatic tape lay-up, and resin transfer molding (RTM). As a result of the manufacturing process, various types of damage might evolve in the laminate. Some of these damages are clearly visible and are detected during inspection. However, some can go undetected and such occurrences must be accounted for [21]. Hence, manufacturing method should be considered as a parameter, although it is difficult to define quantitatively [22].

TABLE 1. MATERIAL SYSTEM, LAMINATE CONFIGURATION, AND MATERIAL PROPERTY PARAMETERS

Parameter	Example Values
Material System	
Fiber Type	IM7, AS4
Matrix Type	977-2, 938, 3501-6
Material System	AS4/3501-6, IM6/CYCOM
Laminate Configuration	
Preform Type	Tape, Woven (fabric), Braided, Stitched
Lay-Up Type	Unidirectional, cross ply, angle ply, quasi-isotropic
Stacking Sequence	[0,+45,-45,90]2s, $[0_4/90_4]_{2S}$
Ply Percentages	(33/67/0)
Laminate Thickness (inch)	0.01-0.9
Number of Plies	2.0-108
Manufacturing Method	cure cycles, autoclave, RTM
Fiber Volume Fraction (V_f)	0.1-0.9
Material Properties (Undamaged)	
Unnotched Compression Strength [ksi]	10-200
Elastic Modulus-Compressive (E_c)[ksi]	1-20
Failure Strain [%]	0.1-1.5
Failure Load [lb]	1000-1000000
Strain Energy Release Rate G_{Ic} [lb/in]	0-10
Strain Energy Release Rate G_{IIc} [lb/in]	0-10
Strain Energy Release Rate G_{IIIc} [lb/in]	0-10

The type of preform is important since braided and stitched composites have improved out-of-plane behavior that may retard delamination initiation and growth within the laminate. Other laminate related parameters include lay-up type and number of plies or laminae or more specifically the laminate stacking sequence (LSS) and ply percentages. Laminate thickness is been determined by structural sizing analysis and have been shown to be one of the most dominant parameters in compression after impact damage behavior [23].

To assess residual performance with damage, undamaged laminate properties should be well known. Since compression loading is more deleterious in impacted composite laminates, compressive undamaged mechanical properties are of greater importance. Unnotched compression strength is commonly used in the assessment of compressive strength after impact (CSAI) by indicating strength loss as a percentage of the unnotched strength value. Unnotched compression strength values are reported in terms of either average laminate failure stress or total strain to failure. On the other hand, damage resistance or tolerance is related to the material's interlaminar fracture toughness, G, as indicated by energy release rates, namely G_{Ic}, G_{IIc}, G_{IIIc}. These parameters represent the ability of the resin to resist delamination, and hence damage, in the three modes of fracture. They are also instrumental in assessing the behavior of brittle versus toughened resin systems. A list of baseline laminate material properties is given in table 1.

3.1.2 Structural Configuration.

Impact damage geometry and residual static strength of built-up structures are strongly dependent on structural configuration. Failure modes of built-up structures also depend on their configuration, as their tolerance to impact damage is quite different and better than for small coupons. The configuration and the dimensions of the structure were chosen as parameters to define the size and general appearance of the structure. Structure type is defined as a parameter to distinguish between the structural details such as open holes, curvature, and bolted and bonded joints. The effects of such structural details are important because they constitute the critical points in a composite design. Semimonocoque skin structures are of particular interest to the civil aircraft applications design. Such structural components have either thin skin or a honeycomb sandwich cross-section with stiffeners. The spacing of the stiffeners determines the effective laminate area that is exposed to possible impact as well as the boundary conditions for damaged laminate under compressive loading. Also, if the impact is near a stiffener, the stiffener causes the impact site to be stiffer, i.e., less damage resistant, but the additional redundancy provided by the stiffener allows the material to be more damage tolerant [24]. Therefore, stiffener spacing was also considered as a parameter in damage behavior assessment. Parameters that were selected for this group are listed in table 2.

TABLE 2. STRUCTURAL CONFIGURATION PARAMETERS

Structural Parameters	Example Values
Structural Configuration	Coupon, panel, stiffened panel, honeycomb sandwich
Length of Structure [in]	1.0-10
Width of Structure [in]	1.0-10
Structure Type	flat coupon, shell, notched coupon
Stiffener-Web Spacing [in]	6

3.1.3 Impact Event Related Parameters.

To simulate impact events that are expected to occur during the fabrication and service of composites, impact tests were conducted in a laboratory environment. Impact threats may be categorized by the mass, shape, size, stiffness, velocity, and incidence angle of the impactor. Thus, impact tests are designed by taking these parameters into account to simulate service conditions. The location of impact on the target and the target support conditions are also reported to be consequential [25, 26, 27]. Delfosse, et al. [28] demonstrated the effects of impactor properties on the subsequent damage formation. Resulting damage was found to be a function of impactor mass, and a low mass impact would lead to smaller delaminations at a given impact energy level. On the other hand, impact energy is the most commonly used metric in the damage tolerance and resistance assessment of composite structures. Other metrics that are used as governing parameters are dent depth and damage area. Absorbed impact energy is also important because together with stiffness and support conditions, it defines the amount of damage induced in the laminate. When the impactor hits, the constrained laminate responds with bending and shear deformation. If the bending stiffness is high and the structure is highly constrained with only a small open area, then more energy is transferred to the fibers and matrix, resulting in more fiber breakage, i.e., more damage. A list of impact parameters is given in table 3.

TABLE 3. IMPACT PARAMETERS

Impact Parameters	Example Values
Impact Type	drop weight, air gun
Impact Fixture	SACMA, NASA, BOEING, Custom...
Impact Fixture Length [in]	1-10
Impact Fixture Width [in]	1-10
Impact Event Boundary Conditions	C-C-C-C, C-C, C-C-S-S ...
Impact Energy [ft-lb]	10-120
Absorbed Impact Energy [%]	1-100
Impactor Mass [lb]	0.001-10
Impact Velocity [ft/s]	1-1000
Impactor Diameter [in]	sharp, 0.02-2
Impact Location	Center, ...
Impact Force [lb]	10000-100000
Impact Measure	dent depth, energy

3.1.4 Compression Testing After Impact and Residual Properties.

Compression testing methodology of composites is a well-established area of research. Numerous experimental methods have been proposed due to the dependence of failure modes on the test method [29] and various standards evolved as described in the review paper by Camponeschi, Jr. [30]. These methods can be characterized by fixture type, dimensions, and support conditions. Loading rate is also a factor in the strength of composite laminates. Since mechanical testing is conducted either under load control or displacement control, both rates were considered as parameters in the assessment of residual properties. Many other specific parameters are involved with compression tests, but these are general to the compression testing problem and are not directly related to damage behavior. Hence, the parameters listed in table 4 were selected and grouped together.

3.1.5 Damage Characteristics.

The extent of damage is characterized or measured by dent depth and damage dimensions such as area and diameter. These parameters used to define the damage state of a material are related to nondestructive evaluation (NDE) techniques. As described earlier, behavior under BVID is a critical certification issue and the extent of BVID is defined by dent depth or the energy needed to create the BVID. X-rays are commonly used in damage detection in two dimensions (2D). Accordingly, damage area can be introduced as a damage parameter. However, researchers' findings show that damage accumulation is a three-dimensional (3D) phenomenon and other NDE methods need to be employed to capture the true damage behavior of composites [6]. For clearly visible impact damage and discrete source damage, penetration of the laminate may be of interest because, with penetration, residual properties become comparable to laminate behavior with an open hole. A list of identified damage characteristics parameters is given in table 5.

TABLE 4. COMPRESSION TEST METHOD PARAMETERS

Compression Testing Parameters	Example Values
Compression Test Fixture	SACMA, NASA, BOEING, NASA short block
Compression Test Fixture Length [in]	1-20
Compression Test Fixture Width [in]	1-10
Compression Test Fixture BCs	C-C-C-C, C-C, C-C-S-S ...
Displacement Control [inch/min]	0.01-0.1
Load Control [lb/min]	100-20000

TABLE 5. DAMAGE CHARACTERISTICS AND RESIDUAL MATERIAL PROPERTIES PARAMETERS

Parameter	Example Values
Damage Characteristics	
Damage Diameter [in]	0.1-10
Damage Area [in^2]	0.1-10
Dent Depth [in]	0.01-0.6
Penetration	yes/no
Material Properties (Damaged)	
Compression Strength After Impact [ksi]	10-200
CSAI as % of UCS	0-100
Residual Compression Modulus (Ec) [msi]	1-20
Residual Failure Strain [%]	0.1-1.5
Failure Load After Impact [lb]	1000-1000000

3.1.6 Other Information Related to the Impact Behavior.

Other parameters that are not specific to the impact damage behavior have been collected in a separate group. These pieces of information were not used in the parametric studies, but they might be needed or required in order to evaluate the results of these studies (table 6).

TABLE 6. OTHER PARAMETERS THAT AFFECT BUT NOT DIRECTLY RELATED TO IMPACT DAMAGE

Supplements Parameter	Example Values
Manufacturing Information	Autoclave recommended curing cycle information
Environmental Conditions	RTD (room temperature, dry)
NDE Method	Ultrasonic inspection
Compression Test	50-kip closed-loop servocontrolled hydraulic fatigue test stand

One such set of parameters is the details of the manufacturing processes. The number of parameters involved in the processes are so many that a different database is required. Some details of the process might be needed for the damage evaluation. Therefore, recording of these details is left to user discretion and defined as supplementary. The effects of the service environment on the performance of composites are well known. The environmental conditions, temperature and moisture content, should be known in order to evaluate an experimental result and therefore constitute another data set. Another set is the parameters of NDE methodology. The damage that occurs as a result of the impact event can be characterized by NDE methods. To understand the damage and assess detectability, information about the NDE method is necessary. Additional information about the mechanical testing procedure might be needed in the interpretation of damage tolerance, i.e., CSAI, such as the locations of strain gages, gripping specifics, and testing equipment information.

3.2 FATIGUE BEHAVIOR.

The durability of a structure is defined as its ability to maintain mechanical performance throughout its service life. Durability is an economic consideration since maintenance, repair, or modification costs over the service life depend on maintaining adequate durability. In composites, delamination is the main damage growth mechanism under service loading making composites more sensitive to compression-dominated fatigue loading. The growth and accumulation of delaminations through the laminate thickness is often the sequence of events that leads to failure and the loss of structural integrity. Fastener hole wear caused by high bearing stresses is another failure mode that occurs under fatigue for aircraft structures in service [21].

Since composites have flat S-N curves and high fatigue thresholds, their fatigue sensitivity is less than metallic structures. The latter is also due to the fact that strain allowables in aircraft composite structures are held at relatively low values compared to their static ultimate failure strains. However, as the allowables envelope is stretched, the frequently observed wide scatter in data becomes a problem in assessing the durability of the structure. Certification of composite structures for airworthiness involves such considerations.

A thorough parameter identification study for fatigue design of composites has been conducted. Terminology used in reference 21 has been adopted and used throughout this study to avoid confusion. The identified parameters have been grouped together. The following sections describe the groups.

3.2.1 Material System and Laminate Configuration.

The effects of the material system on the fatigue behavior of composite laminates occur from two different variations, fiber and matrix materials and the stacking sequence of the laminate. Therefore, both the fiber-matrix architecture at the lamina level and the specific properties at the laminate level should be considered.

To investigate the effect of stacking sequence, Ratwani and Kan [31] conducted experiments on notched 16-ply AS4/3501-6 graphite/epoxy laminates and concluded that the failure mode in composites changed with the change in stacking due to the stress redistribution within the laminate. In laminates containing 0° plies with an open hole, matrix cracks (called splits) appear in the 0° plies inducing delaminations. The growth and shape of the delaminations depend on the stacking sequence. Stinchcomb, et al. [32] also indicated that the mode and extent of damage in multidirectional laminates were governed by the stress states in the constituent plies and their relationships to the respective strengths.

Komorowski, et al. [33] studied compression dominated fatigue of 18-ply AS4/3501-6 and IM6/5245C graphite/epoxy laminates with two different stacking sequences of $[\pm45/0_2/90/0_2/-45/45]_S$ and $[90/(0/45)_2/(0/-45)_2]_S$. Even though the latter laminate had a toughened matrix material, results suggested a significantly stronger influence of stacking sequence on compressive failure strength and fatigue life than of material selection. While fatigue life changed more than two orders of magnitude between the two lay-ups of the same material, using tougher resin system with same stacking sequence caused a higher fatigue life only by a factor of 10, indicating a strong influence of laminate lay-up on the fatigue behavior.

Composite laminates subjected to compressive loading are prone to delamination. Toughened resins are used in such laminates to reduce the initiation and growth of delaminations. Another approach to improve delamination resistance is through the thickness stitching of the laminate. However, stitching also causes fiber crimping or puncture damage that might degrade fatigue life. Portanova, Poe, and Whitcomb [34] concluded that for open hole specimens, the fatigue strengths of stitched and unstitched fabric composite and the toughened tape composite were about equal. The fatigue lives of the stitched uniweave composite specimens were reduced compared to tape composite specimens in proportion to their thickness increase.

Manufacturing method is also considered as a parameter under Laminate Configuration in table 7. This is because manufacturing methods have influence on the mechanical properties both at lamina and laminate levels. Various schemes for manufacturing composites exist, including hand lay-up, automatic tape lay-up, RTM, and the cure cycles applied during the manufacturing process directly effect the performance and quality of the composite structure.

In view of these studies and observations, material and laminate data were collected in separate groups, namely Material System and Laminate Configuration. The parameters in each group are presented in table 7.

TABLE 7. MATERIAL SYSTEM AND LAMINATE CONFIGURATION PARAMETERS

Parameter	Example Values
Material System	
Fiber Type	IM7, AS4
Matrix Type	977-2, 938, 3501-6
Material System	AS4/3501-6, IM6/CYCOM
Laminate Configuration	
Preform Type	Tape, Woven (fabric), Braided, Stitched
Lay-Up Type	Unidirectional, cross ply, angle ply, quasi-isotropic
Stacking Sequence	[0,+45,-45,90]2s, $[0_4/90_4]_{2S}$
Ply Percentages	(33/67/0)
Laminate Thickness (inch)	0.01-0.9
Number of Plies	2.0-108
Manufacturing Method	cure cycles, autoclave, RTM
Fiber Volume Fraction (V_f)	0.1-0.9

3.2.2 Baseline Material Properties.

To assess residual performance with damage, undamaged laminate strength properties should be well known. Compression strength of damaged laminate is commonly expressed as a percentage of unnotched (undamaged) compression strength. Unnotched tension and compression strength values are reported in terms of average laminate failure stress or as total strain to failure. Using strain levels is more common in the industry applications since design allowables are determined in terms of strain levels. Notched tensile strength (NTS) and notched compression strength (NCS) values are used in the assessment of baseline strength properties of laminates containing an open hole.

Damage accumulation is related to the material's interlaminar fracture toughness, G, as indicated by energy release properties, namely G_{Ic}, G_{IIc}, G_{IIIc}. These parameters represent the ability of the resin to resist delamination, and hence damage, in the three modes of fracture. They are also instrumental in the behavior assessment of brittle versus toughened resin systems. Baseline laminate material properties chosen under this group are presented in table 8.

TABLE 8. MATERIAL PROPERTIES (BASELINE)

Material Properties (Baseline) Parameters	Example Values
UTS [ksi]	10-200
UCS [ksi]	10-200
NTS [ksi]	10-200
NCS [ksi]	10-200
Tensile Failure Strain [%]	0.1-1.5
Compression Failure Strain [%]	0.1-1.5
E_t [msi]	1-20
E_c [msi]	1-20
Tensile Failure Load [lb]	1000-1000000
Compression Failure Load [lb]	1000-1000000
G_{Ic} (K lb/in)	0-10
G_{IIc} (K lb/in)	0-10
G_{IIIc} (K lb/in)	0-10

3.2.3 Composite Structure.

In structural applications, composite laminates are required to be in different geometric shapes including some discontinuities within the laminate. Also, damage can be induced into the structure prior to fatigue loading, such as impact damage, which would also cause material property degradation. A parameter called "Damage Type" has been defined to provide information about the type of stress raiser in the composite structure. This parameter is complemented by another parameter called "Damage Location" to specify the geometry of the structure. The effects of these geometric stress raisers and other design considerations on the fatigue behavior have been extensively investigated using coupon specimens that contain such shapes. Schütz, Gerharz, and Alschweig [35] compared fatigue properties of unnotched, notched, fastener joint and bolted joint T300/914C graphite/epoxy composite laminates under compression-compression (C-C), tension-compression (T-C), and tension-tension (T-T) cyclic loading. The results indicated that stress concentrations reduce the fatigue strength in the short-life region while their effect disappears in the long-life region of the S-N curve yielding to comparable fatigue limits. It was also shown that in the cases of mechanical joints involving load transfer, progressive lengthening of the hole under fatigue loading was the greatest contributor to failure.

Data from coupon and panel level tests are often used in estimating fatigue behavior of complex full-size structures. However, scale-up effects can be important since stress distribution might be different as boundary conditions and structural dimensions change. No direct data supporting scaling effects in fatigue was available in the composites literature. Tension dominated fatigue tests are not constrained by the coupon gage length. For cases with compressive loads, however, coupons need to have either a low slenderness ratio or be mechanically constrained to prevent buckling. Otherwise, fatigue tests are limited by the compressive instability load. This hindrance can be remedied by the use of thick laminates. Another solution is to reduce the coupon gage length that would result in different coupon dimensions. With this option, it becomes harder to compare the fatigue response of the laminate between compression and tension dominated fatigue since a new dimensional variable is introduced. One other solution is to mechanically constrain the test specimen with side supports to deter out-of-plane buckling. In this case, the type of constraint selected will influence damage initiation and growth, affecting fatigue life and the definition of fatigue failure. Other geometric issues of consideration are noncircular cutouts, stiffener termination, and ply drop offs [36]. For these considerations, parameters were selected and grouped as presented in table 9.

TABLE 9. COMPOSITE STRUCTURE PARAMETERS

Structure Parameters	Example Values
Structural Configuration	Coupon/panel, stiffened panel, honeycomb sandwich
Structure Length [inch]	1.0-10
Structure Width [inch]	1.0-10
Damage Location	center, 0.25 in. off
Damage Type	plain, 0.25 in. hole, 0.50 in. hole, impact

3.2.4 Cyclic Loading and Other Testing Parameters.

Effects of loading parameters on the performance of composite materials have been documented in a number of studies [37, 38, 39]. In essence, it can be said that constant amplitude and block fatigue loading can be characterized by three parameters: cyclic frequency (f), stress ratio (R), and the maximum cyclic stress (S_{max}). The effect of S_{max} is usually represented in terms of a so-called S-N curve, a curve relating S_{max} to the resulting number of cycles to failure. For a fixed value of S_{max}, the extent of excursions is controlled using R. The case of $R = 1$ corresponds to the static fatigue or creep where there is no load variation. $R = -1$ means a fully reversed tension-compression fatigue. The effect of R on fatigue life of cross-ply E-glass/epoxy laminates was studied by Mandell and Meier [40]. By varying the minimum fatigue stress while holding the maximum fatigue stress constant, they showed that the fatigue life, in terms of cycles to failure, decreased with decreasing R, the effect being more pronounced at lower load levels. Researchers also considered the effect of frequency on the fatigue behavior [41, 42, 43, 44]. The results reviewed may be summarized as follows: at low frequency ranges where there is negligible heat dissipation, as the load frequency increases, cycles to failure increase also. As higher frequency ranges are considered this increase is at a slower rate. When there is excessive heat dissipation, however, a reverse trend can be observed.

In actual service, composite laminates are subjected to random or spectrum loading, which is of particular importance to aircraft structures. While most of the fatigue studies on composite materials were based on constant amplitude tests, there have been studies on the effect of variable loading on fatigue life and damage accumulation [45, 46, 47]. Two objectives were sought in these studies: the resolution on the effect of spectrum modification and the validation of fatigue life and damage accumulation. For these studies various loading sets have been generated that simulate the service loads encountered by civilian and military aircraft. Thus, these loading sets are also considered as a parameter for cyclic loading. In light of these studies a group of parameters have been formed (table 10).

TABLE 10. CYCLIC LOADING AND MECHANICAL TESTING PARAMETERS

Parameter	Example Values
Cyclic Loading Parameters	
Load Dominance	T-T, T-C, C-C
Load Type	Const. Amp., lo-hi block, FALSTAFF spectrum, TWIST
Max. Cyclic Stress (S_{max}) [ksi]	-200 - 200
Mean Stress [ksi]	200
Stress Ratio (R)	-10 - 10
Frequency (f)	0.1-40
Number of Cycles (n)	100-1000000
Testing Parameters	
Fixture Type	SACMA, NASA, BOEING, OTHER
Gauge Length [inch]	1-10
Gauge Width [inch]	1-10
Test Boundary Conditions	C-C-C-C, C-C, C-C-S-S ...
Displacement Control [inch/min]	0.01-0.1
Load Control [lbs/min]	100-20000

During fatigue tests, cyclic loading applied can be tension dominated, compression dominated or in the form of tension-compression. Even though testing methods are well-established and standardized for tension dominated tests, numerous experimental methods have been proposed for compression tests of composite materials due to the dependence of failure modes on the test method. These methods can be depicted by fixture type, dimensions, and support conditions. Therefore, these parameters are identified and grouped together separately in addition to loading parameters (table 10). Many other parameters involving gripping, aligning, and specimen mounting are considered in compression tests, but these are general to the mechanical testing problem and are not directly related to damage behavior under cyclic loading.

3.2.5 Residual Properties, Damage, and Life Assessments.

As mechanical properties change due to damage accumulation and stress redistribution during cyclic loading, their values are tracked to determine residual strength and stiffness. Life assessments can also be made by measuring the residual values as functions of time, i.e., number of cycles. Similar to the baseline properties, tensile and compressive strength (both in terms of average stress and total strain) and moduli values are considered (table 11).

TABLE 11. RESIDUAL MATERIAL PROPERTIES, DAMAGE, AND LIFE PARAMETER GROUPS

Parameter	Example Values
Residual Material Properties	
Residual Tensile Strength [ksi]	10-200
Residual Compression Strength [ksi]	10-200
Residual E_t [msi]	1-20
Residual E_c [msi]	1-20
Residual Failure Strain-t [%]	0.1-1.5
Residual Failure Strain-c [%]	0.1-1.5
Damage	
Ply for Crack Density	90, 45, -45
Crack Density	0-100
Split Length [inch]	0-10
Delamination Area [sq in]	0-10
Life	
Cycles to Failure (N)	100-1000000

In durability assessment of composites, damage accumulation under sustained loads is important rather than final failure. Hence, damage parameters such as ply crack density, delamination area, and split length (in the case of notched laminates) are considered and grouped together (table 11). On the other hand, total number of cycles to failure is an essential information from a design point of view and is considered as a separate entity (table 11).

4. INFORMATION SYSTEM FOR DAMAGE TOLERANCE OF COMPOSITES.

An information system called *DamTol* has been developed to incorporate the design data of impact damage behavior of polymer matrix composites. The operating environment is Microsoft Access 97 Relational Database Management System (RDMS). Visual Basic for Applications subroutines and Structured Query Language (SQL) commands have been generated and are used for the data retrieval and expert solution interfaces. This section discusses the rationale behind *DamTol*, its architecture, the implementation issues, and presents several case examples that demonstrate the practical use of the system.

A study was conducted on information systems aimed at combining the two tools of information processing by applying some of the expert system development techniques to a relational database structure. Besides offering standard database functions, *DamTol* also has a module, called Expert Solution, that calculates the similarity between the specified input parameter values and cases that are stored in its database. The capability of this module has been expanded to handle low confidence inputs. The output is either CSAI or damage geometry values with overall confidence levels.

4.1 *DamTol* ARCHITECTURE AND STRUCTURE.

Data generated through laboratory experiments as well as data collected through an extensive literature survey have been stored in *DamTol*. The data are divided into 102 different fields and grouped under 14 tables. These tables and brief information about their content are listed in table 12. Most of the data fields were determined by identifying and considering the parameters of impact damage behavior of composites that were discussed in section 3. Others are used for storing supporting information such as reference names, document title, etc.

TABLE 12. BRIEF DESCRIPTION OF TABLES IN *DamTol* DATABASE

Table	Description
1. Main	Each record of this table holds the primary key of nine other tables to define a composite design data set in the database.
2. MaterialSystem	Each record of this table holds a unique material and contains the industrial name and the supplier of a composite material.
3. MaterialPropertyUndamaged	Each record of this table holds a unique set of undamaged material properties for a material system as reported by the document.
4. Structure	Each record of this table defines a unique structure for a given composite material.
5. LaminateConfiguration	Each record of this table defines a unique set of laminate configuration. The set consists of parameters such as lay-up type and stacking sequence.
6. MaterialPropertyDamaged	Each record of this table defines a unique set that describes the material properties of a composite with damage.
7. CompressionTestingParameters	Each record of this table defines a unique set that describes the compression testing environment such as the fixture's geometry.
8. ImpactParameters	Each record of this table defines a unique set that describes the impact testing environment such as impact type and impact fixture.
9. DamageCharacteristics	Each record of this table defines a unique set that describes the damage geometry of a laminate.
10. DataSource	Each record of this table holds the primary key of three other tables that together define the source of data.
11. DataEnterer	Each record of this table is a unique set that describes an individual who has entered data into the database.
12. References	Each record of this table holds a unique set for the reference information of a paper.
13. Authors	Each record of this table contains a unique set that describes the name of an author of one or more documents in the database.
14. Notes	Information that could not be normalized in the database are collected in a record of this table for each document.

The normalization rules described in section 2.3.2 were applied to *DamTol*. However, in a few instances, normalization rules were broken in order to retain all pertinent information in a document. In other words, even though 102 fields were created in the database to store the essential data in the majority of documents, some fields were left outside of the normalization process. The *Notes* section of the database was created as a memo field so that users can enter any other important information in text form that is not directly related to impact damage.

Once tables were created, relationships among these tables were established. The *DamTol* database consists of two main tiers. The first tier is for recording the source of the information being entered and consists of the following tables: *DataSource*, *DataEnterer*, *References*, *Authors*, and *Notes*. It should be noted that each record in *DataSource* identifies a single document as a source of data through a one-to-one relationship (figure 1). These relations are used to minimize redundant information according to the normalization rules. The information about a given data enterer is recorded only once and given an ID in the *DataEnterer* table. This ID is then used in the *DataSource* to uniquely refer to the person who enters the data. A similar explanation holds for developing separate *Notes* and *References* tables and then using relations to refer to the appropriate information in the *DataSource* table.

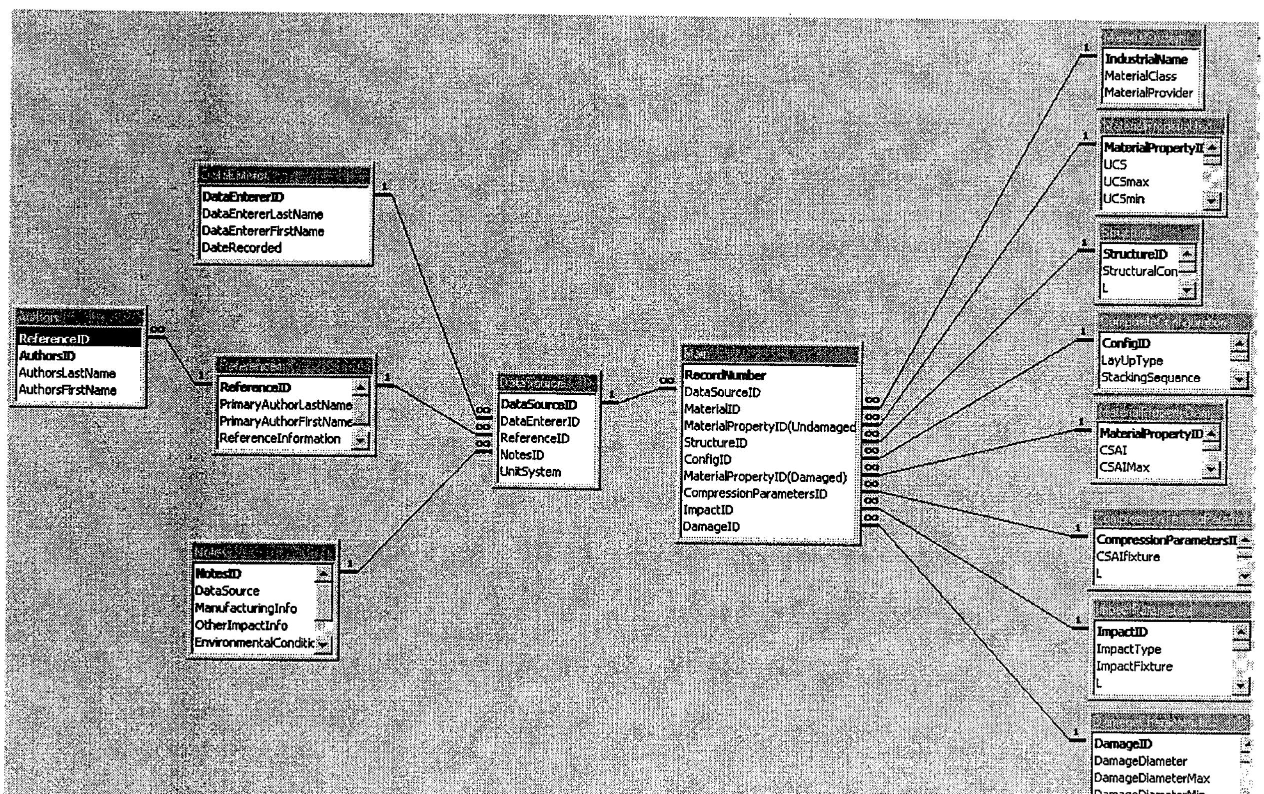


FIGURE 1. DATABASE STRUCTURE AND RELATIONSHIPS

The second tier of the database consists of tables that are used to record the contents of each document, including experimental procedure and results. *DamTol* is structured to capturing the method by which experiments are performed. Generally, a given experiment consists of studying the dependence of one parameter on another parameter and tests are conducted by varying only one desired parameter while keeping all other variables constant. To overcome redundancy problems, related fields were grouped together to form several tables using the study described in section 3.2. The tables were named *MaterialSystem, MaterialPropertyUndamaged, Composite Configuration, Structure, ImpactParameters, MaterialPropertyDamaged, Damage Characteristics,* and *CompressionTestingParameters*. Records of these tables were then assigned a unique ID, effectively defining pertinent parameter values. Then, another table called *MAIN* was created that combined the ID fields of the tier-two tables to define a data set, called a test. Records in the *MAIN* table have a one-to-one relationship with individual tests entered from a given document. The advantage of this scheme is that experimental conditions are defined only once, and are referred to by their ID numbers in the records of the *MAIN* table.

4.2 IMPLEMENTATION AND SYSTEM DESCRIPTION.

Having developed the structure of the database, user interfaces were created next to present and retrieve information from the user. There are three user interfaces providing three options. The first option is the data entry interface which allows the user to enter new sets of data. The second option is the data retrieval interface, an environment to conduct parametric studies. The third component is the comparison interface called Expert Solution, intended to aid in the assessment of the extent of similarity between data sets. Once *DamTol* is launched, a switchboard appears containing links to the three options (figure 2). In the following sections, these options are explained in detail.

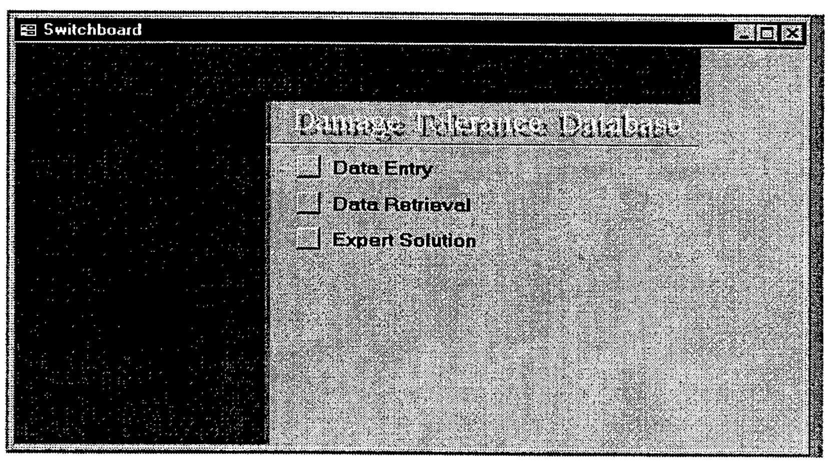


FIGURE 2. *DamTol* SWITCHBOARD

4.2.1 Data Entry Interface.

The Data Entry Interface provides a series of forms to guide and facilitate the process of entering or modifying data. For all entries, help boxes have been created that appear if the cursor is placed on an entity. The help boxes contain descriptions for the entity as well as units for numeric entries and example values. This way, learning to use the system has been made easier and possible terminological confusion has been eliminated. While there are two main tiers in the structure of the database, Data Entry is also divided into two parts as Page One and Page Two.

Page One is based on the first tier of the database, namely *DataEnterer*, *References*, *Authors*, and *Notes* tables (figure 3). The user starts the data entry process by entering identification information, such as full name and date. Other fields to complete are about the source of the data. Fields of the *Notes* section serve the purpose of storing any other important information that is not directly related to impact damage behavior analysis. The fields of *Notes* are Manufacturing Information, Environmental Conditions, NDE Methodology, Data Source, Other Impact Information, and Compression Testing. The *Notes* fields are also monitored by the database to see if there is a focus on a parameter other than the ones in the database. If a specific piece of data is consistently reported by most documents, it should be incorporated as a separate field in an appropriate table. As a result, *Notes* fields help supplement the parameter extraction study reported in section 3. Clicking the navigation buttons allows the user to move through papers to modify or enter data in the first tier.

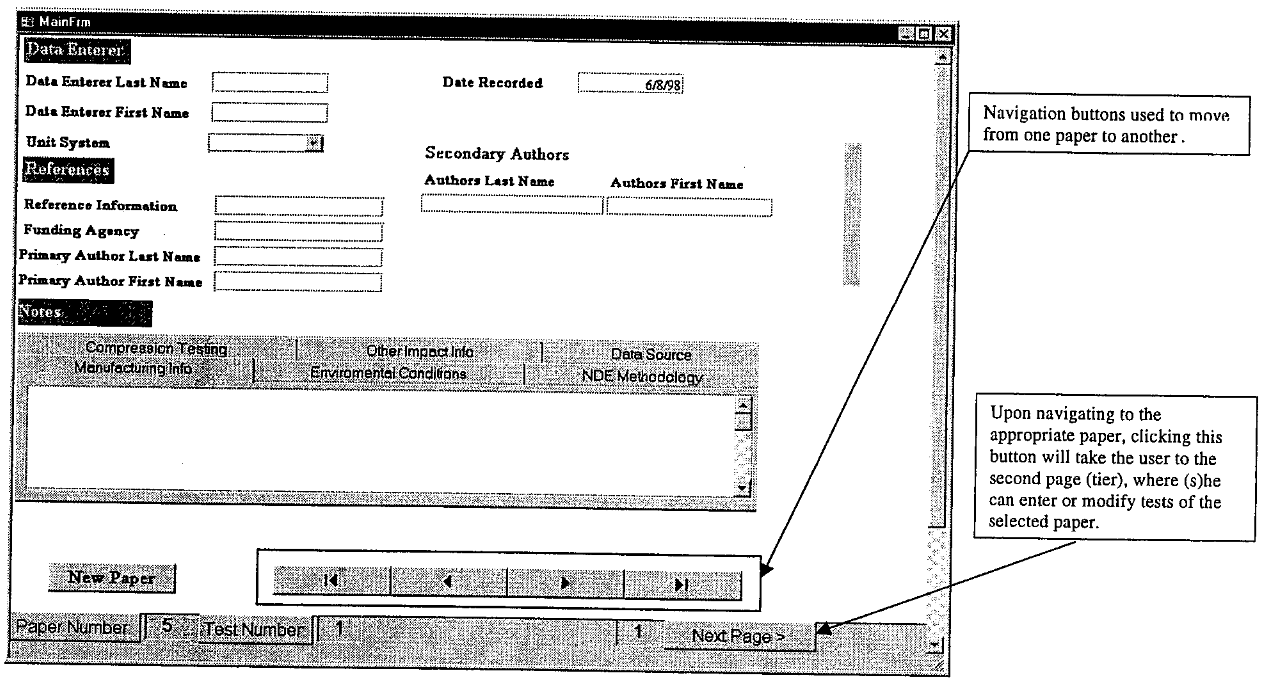


FIGURE 3. PAGE ONE OF DATA ENTRY INTERFACE

After a user has navigated to a particular publication (Data Source) in the first page, additional information may be entered or existing information modified on Page Two. This page contains tests and experimental results in eight cascaded folders for the publication selected in Page One and is based on the second tier of the database (figure 4). Within each folder, the user finds pertinent parameters and starts assigning values either by looking at and selecting previous entries or by typing in a new value. Most of the parameter fields contain pull-down menus enabling easy viewing of the previously entered values. The pull-down menus are updated each time a new value is entered. As the user moves to a different test, contents of the six folders are replaced with the data of the current test. Any time during data entry, the user can click on the Previous Page button, to go back to the first page. Once in the first page, the user can navigate to any other publication and repeat the above process for entering new or modifying existing data.

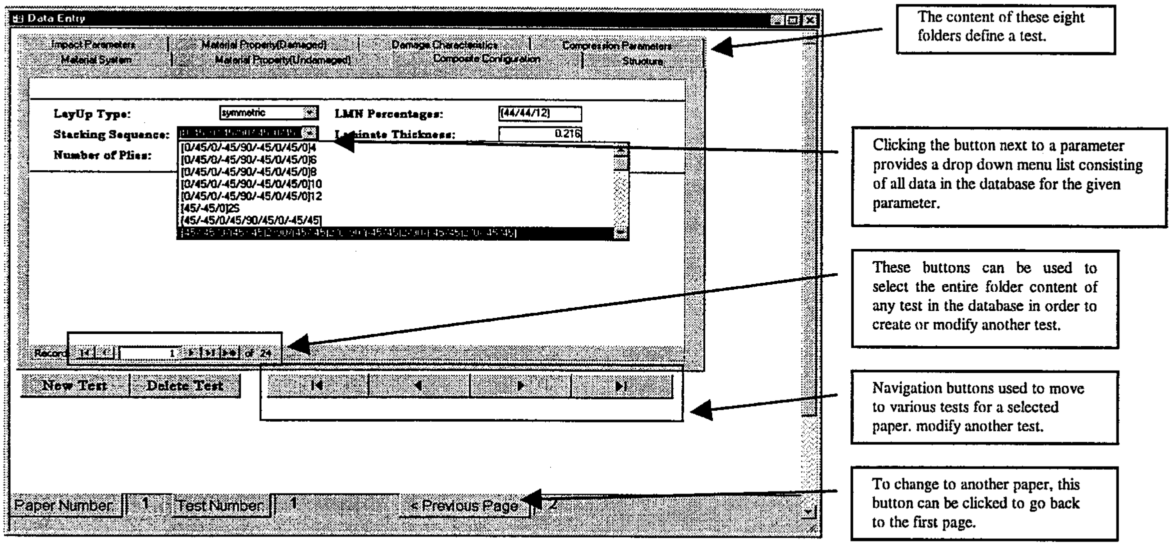


FIGURE 4. PAGE TWO OF DATA ENTRY INTERFACE

4.2.2 Data Retrieval Interface.

The Data Retrieval interface allows the user to query the database for the desired information. The data retrieval form consists of two main parts; the top section of the form is designed for building the search string for the information and the bottom section for presenting the results of the search (figure 5).

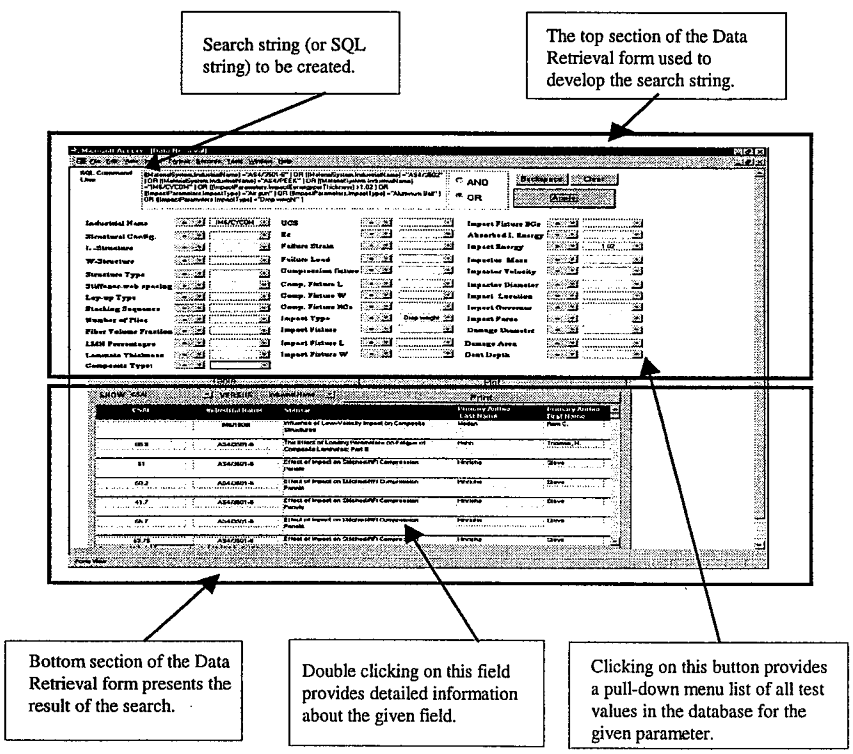


FIGURE 5. DATA RETRIEVAL INTERFACE

Of the 102 data fields, 37 are available to be chosen by the user in the data retrieval process. Not all fields are available because some of the fields in the system are for supporting data such as maximum and minimum values and standard deviation for key parameters. Also, data source information and *Notes* fields are not applicable to parametric studies. Therefore, such fields are not available in the data retrieval process. The user can use the 37 specified fields to create a search string. These fields and a representative value for each field is presented in table 13.

TABLE 13. FIELDS AND EXAMPLE VALUES FOR DATA RETRIEVAL

Parameter Description	Field Name	Representative Value
Material System	Industrial Name	AS4/3501-6
Coupon/Panel/Subcomponent/Component	Structural Configuration	
Length of structure	L-Structure	10 inches
Width of structure	W-Structure	5 inches
Flat/curved/stiffened (structural geometry)	Structure Type	
Stiffened structure web spacing	Stiffener-Web Spacing	
Type of preform used in laminate	Preform Type	Tape
Lay-up type of composite	Lay-Up Type	Quasi-iso
Stacking sequence of composite	Stacking Sequence	[0/45/-45/90]2S
No. of plies in the laminated composite	Number of Plies	16
Fiber volume fraction of composite	Fiber Volume Fraction	63
0/±45/90 ply %'s in the composite laminate	LMN Percentages	(25/50/25)
Thickness of the laminate	Laminate Thickness	0.080 inches
Ultimate compression strength	UCS	98 ksi
Elastic modulus (compression)	Ec	7.0 msi
Failure strain	Failure Strain (%)	
Failure load	Failure Load	
Compression test fixture type	Compression Fixture	NASA ST-1
Compression test fixture length of composite	Compression Fixture L	10
Compression test fixture width of composite	Compression Fixture W	5
Boundary conditions of the compression fixture	Compression Fixture BCs	C-C-S-S
Type of the impact test	Impact Type	Drop Weight
Fixture for impact test	Impact Fixture	NASA ST-1
Length of the fixture for impact test	Impact Fixture L	5
Width of the fixture for impact test	Impact Fixture W	5
Boundary conditions of the impact test fixture	Impact Fixture BCs	C-C-C-C
Absorbed impact energy during impact	Absorbed Impact Energy	80%
Impact energy	Impact Energy	7.8 ft-lb.
Mass of the impactor	Impactor Mass	0.66 lb.
Velocity of the impactor	Impactor Velocity	220 ft/s
Diameter of the impactor	Impactor Diameter	0.5 in.
Location of impact on the composite structure	Impact Location	Center
Incremental (governing) parameter in impact test	Impact Governor	Impact Energy
Impact force	Impact Force	
Diameter of damage created by impact	Damage Diameter	0.1 in.
Area of damage created by impact	Damage Area	0.0314 sq. in.
Depth of damage created by impact	Dent Depth	0.01 in.

The search string is based on SQL standard. Here the user specifies values by choosing from the pull-down menus for one or more variables (figure 6). It is important to note that specification of a variable does not necessarily mean equating a variable to a value. Instead, a variable can be given a value by using Like, <, >, <=, or >= operators. The user also has the option to choose between logical operators AND and OR to link the conditions. The search string is generated automatically by the program as the user chooses operators and assigns values and is visible to the user at the top of the window. BACKSPACE and CLEAR buttons allow for changes or restart. The search string can also be entered directly by the user in the SQL Command Line field instead of specifying values from pull-down menus.

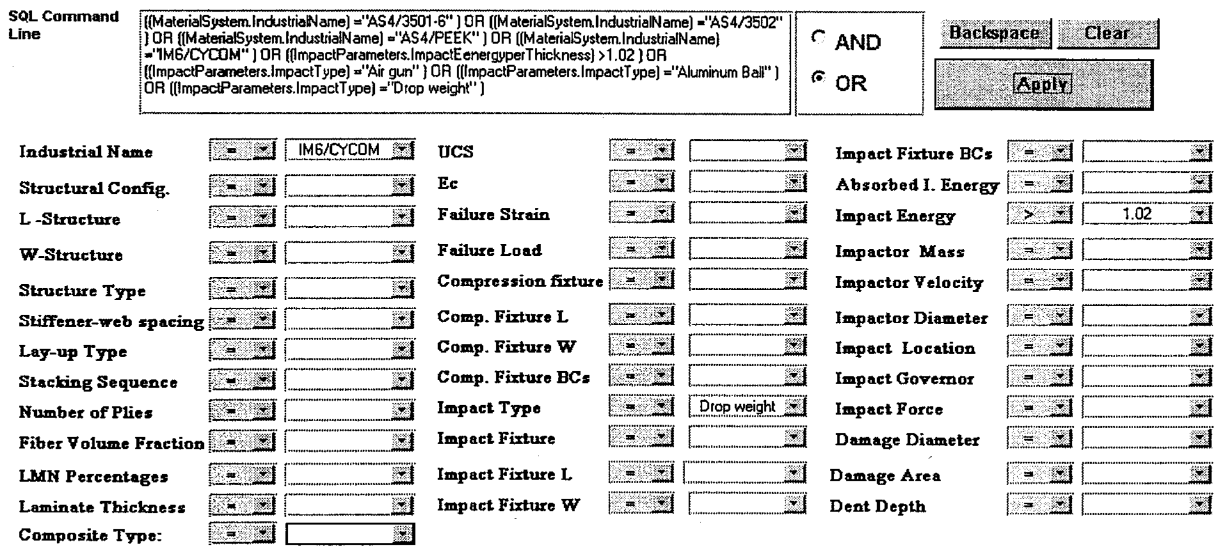
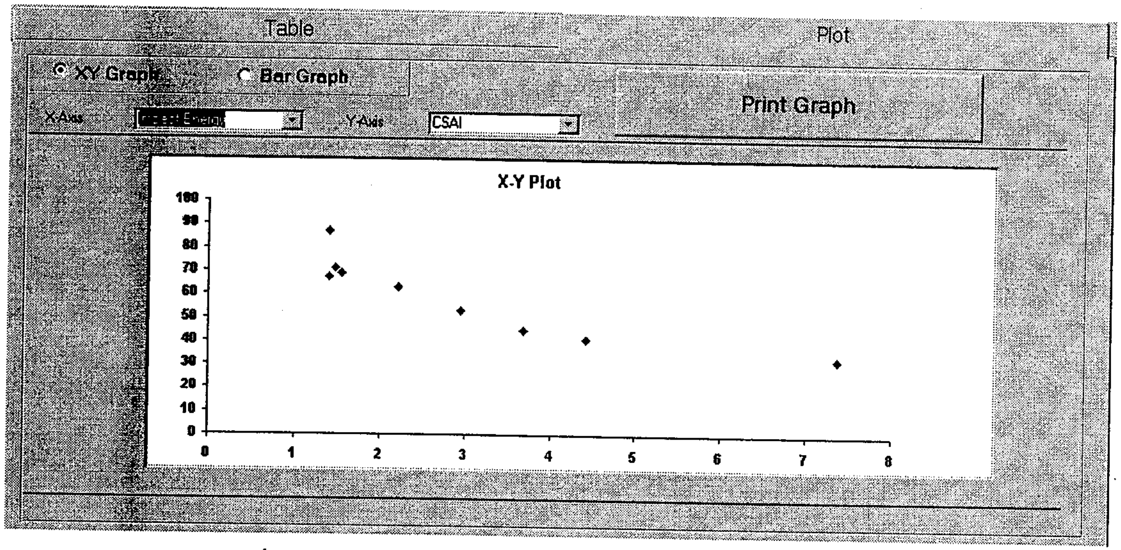


FIGURE 6. BUILDING A SEARCH STRING AND QUERYING WITHIN THE DATA RETRIEVAL INTERFACE

Once the appropriate search string (i.e., SQL string) is created and the APPLY button is clicked, the program finds all the records in the database that satisfy the search string. The results can be viewed either as a table or a graph. Two different chart types are used to handle both numeric vs. numeric and alphanumeric vs. numeric plots. These are called the *X-Y Graph* and the *Bar Graph*, respectively (figure 7). Within each option there are two pull-down menus that allow the user to choose the horizontal and vertical axes of the graph. As a result, the user is equipped with a tool that provides instant comparison of any two variables under any set of constraints.

In the Table folder, results are presented in five columns. The first two columns display the parameters chosen by the user. The third through fifth show information about the source documents from which the queried data is taken. An important feature of this section is that for any search result more detailed information in the form of eight cascaded folders can be obtained by simply double clicking on the source document (figure 8).

(a)



(b)

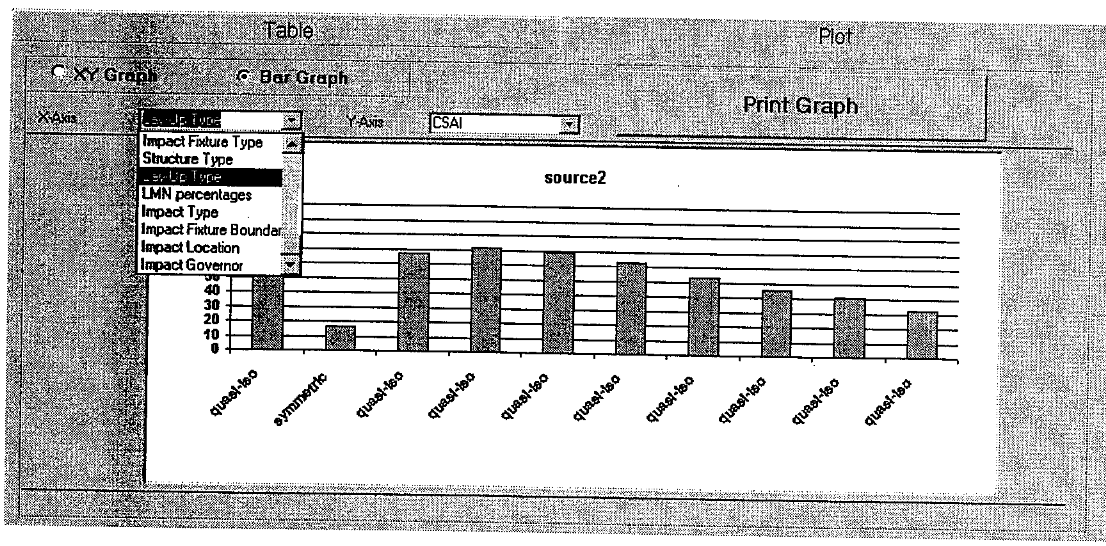
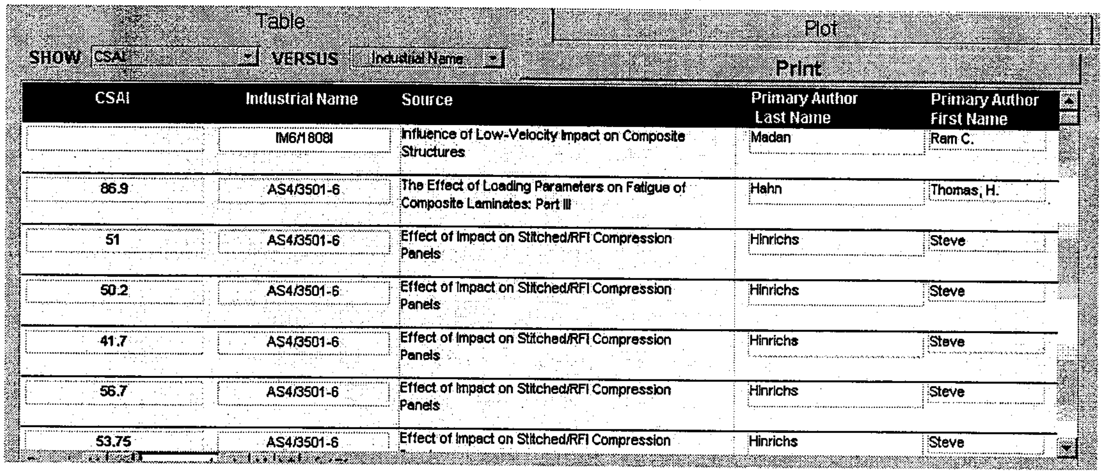


FIGURE 7. (a) X-Y PLOT INTERFACE AND (b) BAR GRAPH INTERFACE

Using the Data Retrieval Interface, one can rapidly conduct parametric studies on the damage behavior of composites. By changing the conditions and values of parameters, relationships between different parameters can be assessed. Gaps in the data can be identified using the graphs generated by the system. Also, it is likely that an error generated in data entry would be conspicuous in the graphs.

(a)



(b)

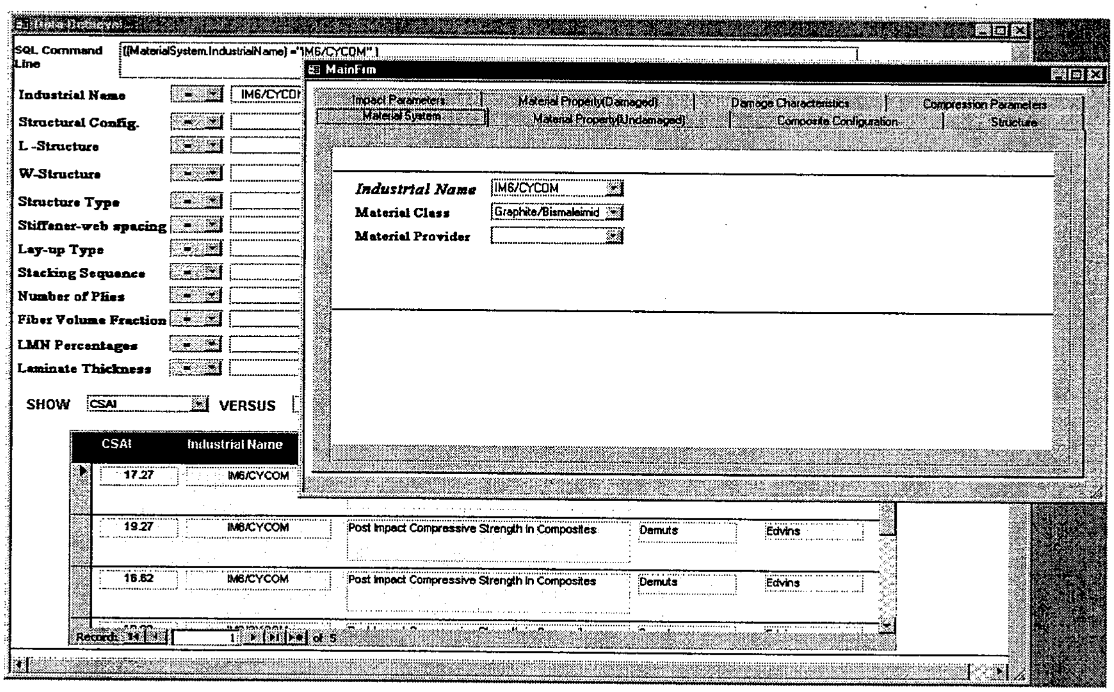


FIGURE 8. (a) RESULTS TABLE INTERFACE AND (b) POP-UP WINDOW FOR VIEWING ALL DATA BEHIND THE CHOSEN RECORD

4.2.3 Expert Solution Interface.

The third interface in the *DamTol* switchboard is intended to assist the user when none of the stored records can exactly satisfy the requirements imposed. The Expert Solution selects those records that match the user requirements most closely. The Expert Solution interface can be used to predict the damage tolerance and damage resistance of a new composite structure. It can also be used to assess similarity between test cases. In both ways, results are obtained by using data stored in the database and by incorporating the user's knowledge and expertise. To fulfill the objectives, the system compares values of the user's composite design parameters with that of composite designs existing in the database and arrives at conclusions by using the embedded reasoning mechanism.

The top 34 parameters listed in table 13 were used for the Expert Solution. Every parameter has a pull-down menu that lists all values stored in the database for that parameter. Using these pull-down menus, the user chooses a value that matches his/her design value most closely (figure 9).

(a)

(b)

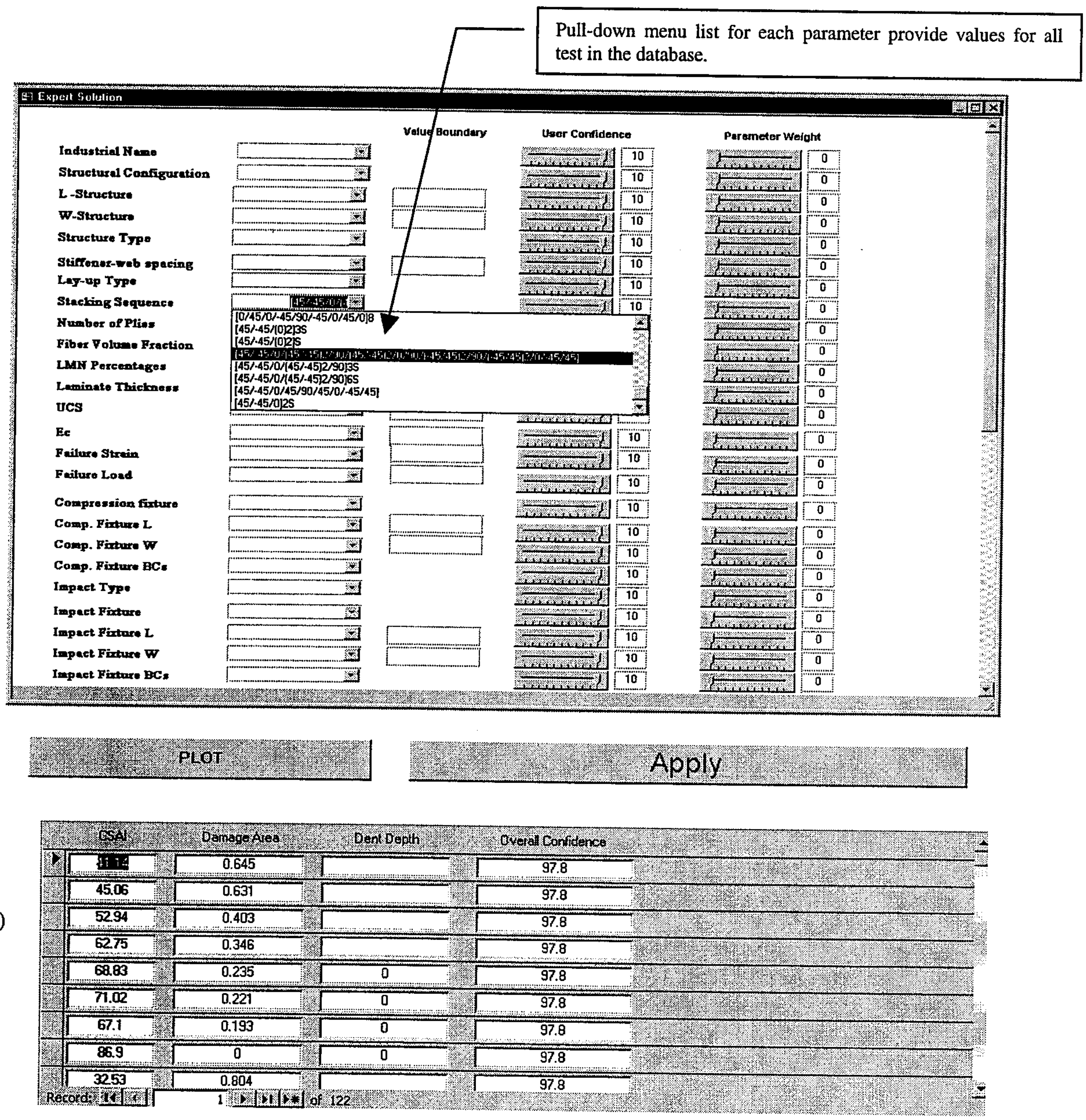


FIGURE 9. EXPERT SOLUTION (a) VALUE SELECTION INTERFACE AND (b) RESULTS TABLE

Due to numerous parameters affecting composite damage tolerance and damage resistance, having a composite design record in the database that would exactly match the user's composite design is not likely. Therefore, the user's knowledge and judgment are utilized to present results that are similar to the user's requirements. To enable such similarity output, User Confidence and Parameter Weight variables are created for each field in order to capture the user's judgment.

For each value chosen, the user can assign a user confidence (C_i). C_i is a qualitative measure on how well the chosen value matches the user's requirements. In other words, C_i is simply meant to capture the user's "opinion" or "feel of correctness." C_i can take a value from 0 to 10, in which 10 is extremely confident. If a value of 0 is assigned, then this value is considered to be not correct.

The second variable is the Parameter Weight (W_i) for the chosen field. It is a qualitative measure of how relevant the parameter is in satisfying the user requirements. In other words, this value is meant to capture the user's opinion or feel of how critical a given parameter is in the data analysis. W_i also ranges from 0 to 10, where zero is used when the parameter is irrelevant and 10 for the extremely relevant. Once parameter values and the corresponding C_i's and W_i's are specified, the similarity of all data sets in the database to the user's design can be evaluated.

For the evaluation process, a reasoning mechanism has been developed. The following expression for each data set in the database is evaluated as a measure of similarity:

$$C_{Total} = \frac{\sum_{i=1}^{N} W_i \times C_i \times B_i}{\sum_{i=1}^{N} W_i} \tag{1}$$

where N is the number of fields specified, W_i is the weight of the chosen field, C_i is the user confidence of the value selected for the chosen field, and B_i is the Boolean variable. The system assigns a value of zero to B_i if the i-th field does not match the user's selection or if it is not specified. Otherwise, a value of 1 is assigned. C_{Total} is the overall confidence of the composite design case.

The Boolean variable (B_i) is used for a direct comparison of two data values. When the system compares a data set in the database with the user's specifications, all fields are examined one at a time. For a given data set in the database, those fields that have the same value as ones specified by the user will be assigned a B_i value of one; otherwise, a value of zero is assigned. If the B_i of all fields in the database were simply summed, the addition would represent the number of fields that have the same value as those of the user's requirements. While this sum could be used as a measure of similarity, it would have two important deficiencies. Firstly, it does not address how strong the dependency of a given parameter is on the result. Secondly, it does not take into account for values that were similar to the given values, but not be an exact match. To overcome these limitations, variables W_i and C_i were developed as described. Hence, it is easy to realize that equation 1 simply represents the weighted average of user confidence for similarity of new and existing data in the database.

Aside from user confidence and parameter weight variables that are instrumental in the similarity analysis, a lower and upper bound capability for the numeric parameters has been developed to reduce the rigidity of comparison. The user can enter a numeric value to define a range with these bounds. For example, if the impact energy value is chosen to be 3.44 ft-lb, the user can assign a range of 0.56. Consequently for all data sets having impact energy values between 2.88 ft-lb and 4.00 ft-lb, $B_i = 1$ condition will hold, whereas for all other data sets with impact energy values that are out of this range, B_i will be set to zero.

The results presented in table format are CSAI, Damage Area, and Dent Depth for the selected number of data sets in the database that are most similar to the user's design requirements. The results table also includes an overall confidence value that is calculated by equation 1. The values are tabulated in order of descending overall confidence value. Here, the user can enter a threshold value and only the cases that have values above the entered threshold will be displayed. The overall confidence value can be plotted versus any of the three parameters reported as results.

By looking at CSAI, the user can make similarity assessments for damage tolerance behavior as the CSAI measures residual strength. On the other hand, Damage Area and Dent Depth can be used for damage resistance behavior comparison. To view more data for a specific case in the results table, the user can click on that line. A window with eight cascaded folders shows all of the supporting data that can be viewed by visiting these folders. This process is very similar to that in Data Retrieval.

5. INFORMATION SYSTEM FOR DURABILITY OF COMPOSITES.

An information system called *Durability* was developed to incorporate the fatigue design data of polymer matrix composites. The operating environment is the Microsoft Access 97 RDMS. Visual Basic for Applications subroutines and SQL commands were used to support the data retrieval and data comparison interfaces. This section discusses the system characteristics and use of the *Durability* information system. Implementation issues and several case examples that demonstrate the practical use of the system are included.

Since the study conducted on information systems was aimed at combining the two tools of information processing by applying some of the expert system development techniques to a relational database structure, *Durability* is also a hybrid system. Besides offering standard database functions, *Durability* also has a module, called Expert Solution, that calculates the similarity between the specified input parameter values and cases that are stored in the database. The capability of this module has been expanded by the embedded reasoning mechanism described in section 4.2.3.

5.1 *Durability* ARCHITECTURE AND STRUCTURE.

Fatigue data collected through laboratory experiments as well as data found in the composites literature have been stored in *Durability*. The data are divided into 107 different fields and grouped under 15 tables. These tables and a brief description of their content are listed in table 14. Most of the data fields were determined by identifying the parameters of fatigue behavior and durability design of composites that were discussed in section 3.2. Other fields are also used for storing supporting information such as data sources and data entry specifics. The parameters were selected and grouped to create a conceptual data model. This model was implemented under the Microsoft Access 97 environment to form a relational database structure so that the information system could expediently accommodate experimental data entered into the system.

TABLE 14. BRIEF DESCRIPTION OF TABLES IN *Durability* DATABASE

Table	Description
1. Main	Each record of this table holds the primary key of 14 other tables to define a unique dataset in the database.
2. MaterialSystem	Each record of this table defines a unique material and contains the industrial name and supplier information.
3. Baseline Material Properties	Each record of this table holds a unique set of static material property information as reported by the data source for a material system.
4. Structure	Each record of this table defines a unique composite structure including damage type.
5. LaminateConfiguration	Each record of this table defines a unique laminate configuration. The set consists of such parameters as lay-up type and stacking sequence.
6. Residual Properties	Each record of this table defines a unique set that describes the residual mechanical properties of a composite material.
7. Testing Parameters	Each record of this table defines a unique set that describes the testing environment such as fixture geometry and gage dimension.
8. Cyclic Loading Parameters	Each record of this table defines a unique set that describes the cyclic loading environment including number of cycles.
9. Damage	Each record of this table defines a unique set that describes the geometric damage accumulated in a test.
10. Life	Records of this table are cycles-to-failure information for the considered experiments.
11. DataSource	Each record of this table holds the primary key of four other tables that together define the source of a set of data.
12. DataEnterer	Each record of this table is a unique set the describes an individual who has entered one or more documents into the database.
13. References	Each record of this table holds a unique set that records the reference information of a paper.
14. Authors	Each record contains a unique set that describe the name of an author of one or more documents.
15. Notes	Important information that could not be normalized in the database is collected in a record of this table for each document.

The normalization rules described in section 4.2 were also applied to *Durability*. As was the case of *DamTol*, the normalization rules are broken in a few instances. The *Notes* section of the database has been created as memo fields so that users can enter any other important information in text form that is not directly related to fatigue behavior.

Once the tables were created, relationships among those tables were established. The *Durability* database also consists of two main tiers. The first tier is for recording the source of the information being entered and consists of the following tables: *DataSource*, *DataEnterer*, *References*, *Authors*, and *Notes*. It should be noted that each record in *DataSource* identifies a single document as a source of data through a one-to-one relationship (figure 10). Specific information about the data-entering user is recorded only once and given an ID in the *DataEnterer* table. This ID is then used in *DataSource* to uniquely refer to the person who entered the data. A similar explanation holds for developing separate *Notes* and *References* tables and then using relations to refer to the appropriate information in the *DataSource* table.

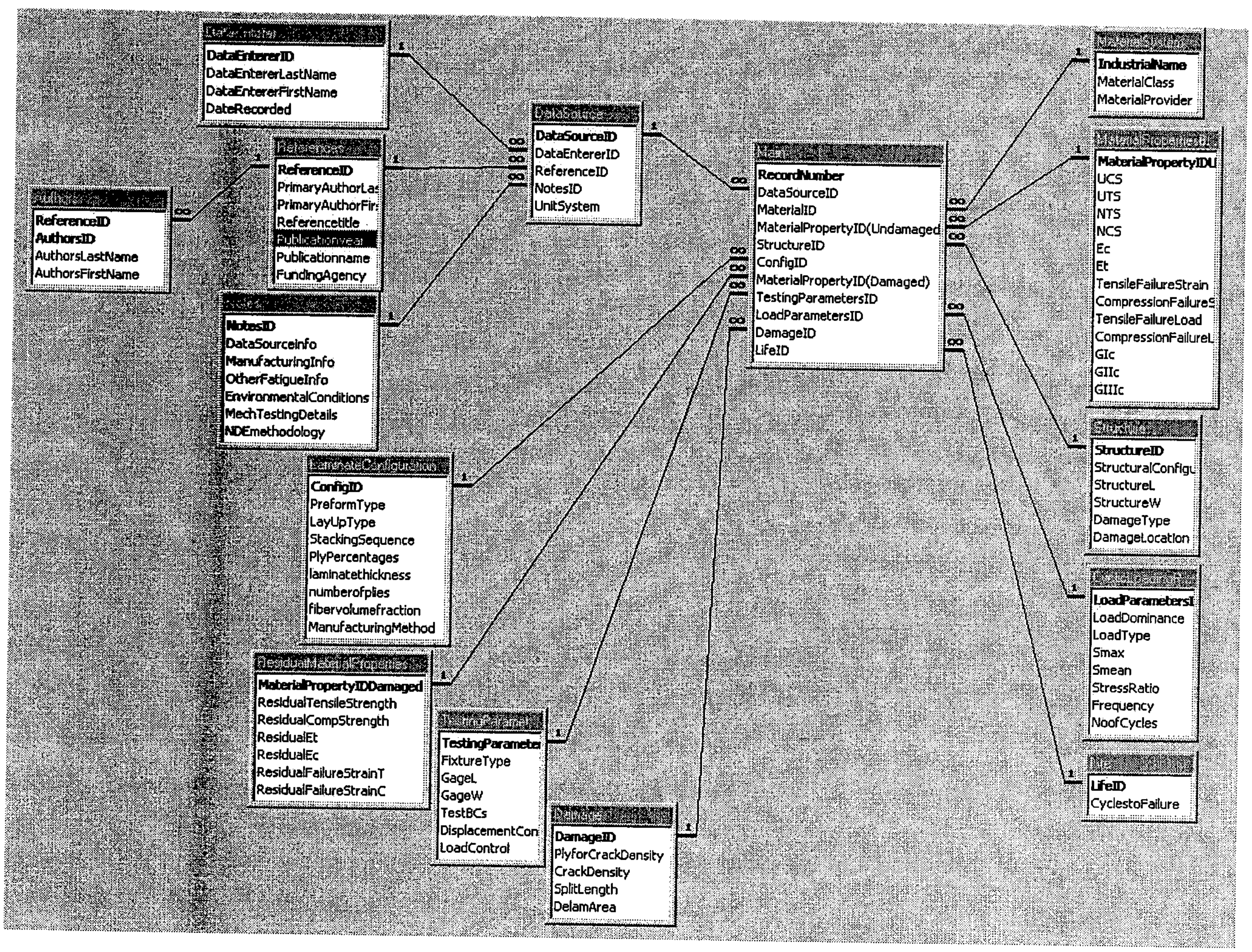


FIGURE 10. TABLES AND THE RELATIONAL STRUCTURE OF THE *Durability* INFORMATION SYSTEM

The second tier of the database consists of tables that are used to record the contents of each document, including experimental procedure and results. *Durability*, with a similar structure as *DamTol*, is geared toward capturing the method by which experiments are performed and using the method to minimize redundant data. The tables of the second tier were named *MaterialSystem, Structure, MaterialProperties (Baseline), LaminateConfiguration, CyclicLoadingParameters, ResidualProperties, Damage, TestingParameters,* and *Life*. Records of the tables that are in tier two were also assigned a unique ID. A table named *MAIN* combines the ID fields of the tier-two tables to define a test.

Thus, *Durability* database shares a similar architecture with *DamTol*. However, the user interfaces developed need to be different, tailored for entering and retrieving fatigue design data. Both the input and the output fields in the user interfaces are substantially different. This leads to building a separate durability database structure. Although it would be possible to accommodate all data under one database, more complicated interfaces would be required causing greater file sizes and memory concerns.

5.2 IMPLEMENTATION AND SYSTEM DESCRIPTION.

The database tables and parameter fields are presented in figure 11. It should be noted that the fields listed in this figure are not all the fields in *Durability*. A total of 107 fields were created where some of these fields are used as metadata to store information about the database structure itself. ID number fields are generated and used as primary keys to establish the relationships between tables. Figure 12 demonstrates how primary keys (ID numbers) are used in defining the relationships for data structuring.

Once the structure of the database was formed, user interfaces were created next to access the database and to retrieve data. Similar to *DamTol*, there are three user interfaces: Data Entry, Data Retrieval, and Expert Solution. When *Durability* is launched, a switchboard appears containing links to the three options (figure 13). In the following sections, these options are explained in detail.

5.2.1 Data Entry Interface.

The Data Entry option provides a series of forms to guide and facilitate the process of entering or modifying data. In designing the *Durability* Data Entry interface, many features of the *DamTol* Data Entry interface were altered. However, the general appearances of the windows were retained. For all entries, help boxes have been created that appear if the cursor is placed on an entity. The help boxes contain descriptions for the entity as well as units for numeric entries and example values. This way, learning to use the system has been made easier and possible terminological confusion has been eliminated. While there are two main tiers in the structure of the database, Data Entry is also divided into two windows as Page One and Page Two.

Page One is based on the first tier of the database, namely *DataEnterer*, *References*, and *Notes* tables (figure 14). The user starts the data entry process by entering identification information, such as full name and date. Other fields to complete are about the source of the data. Fields of the *Notes* section are available for detailed information on the composite structure that is not

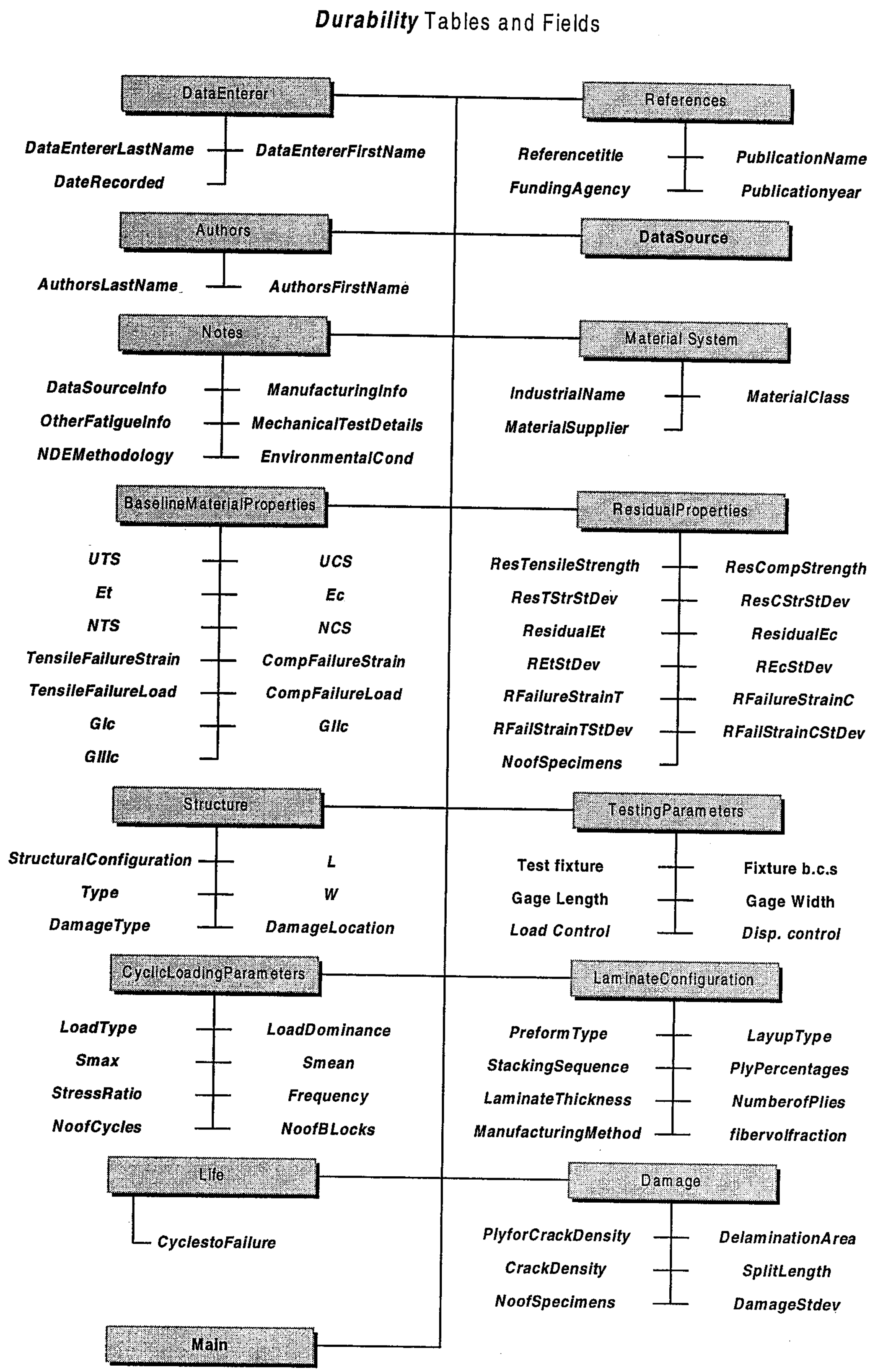


FIGURE 11. TABLES AND FIELDS FOR *Durability* INFORMATION SYSTEMS

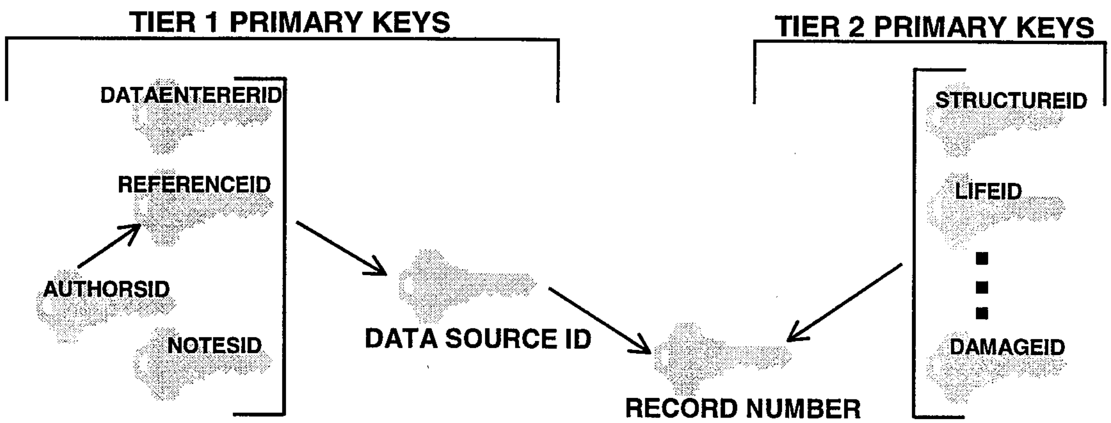


FIGURE 12. PRIMARY KEYS (ID NUMBERS) FOR EACH TABLE ARE DEFINED AND USED FOR ESTABLISHING RELATIONSHIPS AMONG TABLES

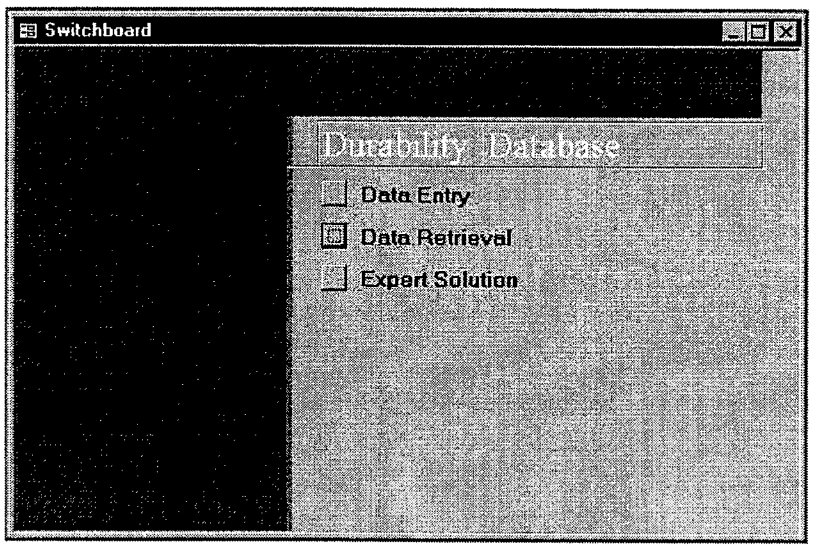


FIGURE 13. *Durability* SWITCHBOARD

directly related to durability design. With fatigue, there are many supplementary parameters that may need to be recorded. However, these parameters and values are not directly used in analysis. One such example may be block information for spectrum loading. The specifics of each block in terms of mean stress, amplitude, stress ratio, and number of cycles is necessary to be able to compare different spectrum loading cases. Also, the ability to take notes gives additional flexibility to the user at the data entry level so that no important data is left out. As a result, *Notes* fields help supplement the parameter extraction study reported in section 3. The fields of *Notes* in *Durability*'s Data Entry are Manufacturing Information, Environmental Conditions, NDE Methodology, Data Source Information, Other Fatigue Information, and Mechanical Testing Details. Clicking the navigation buttons allow the user to move through papers to modify or enter data for the first tier.

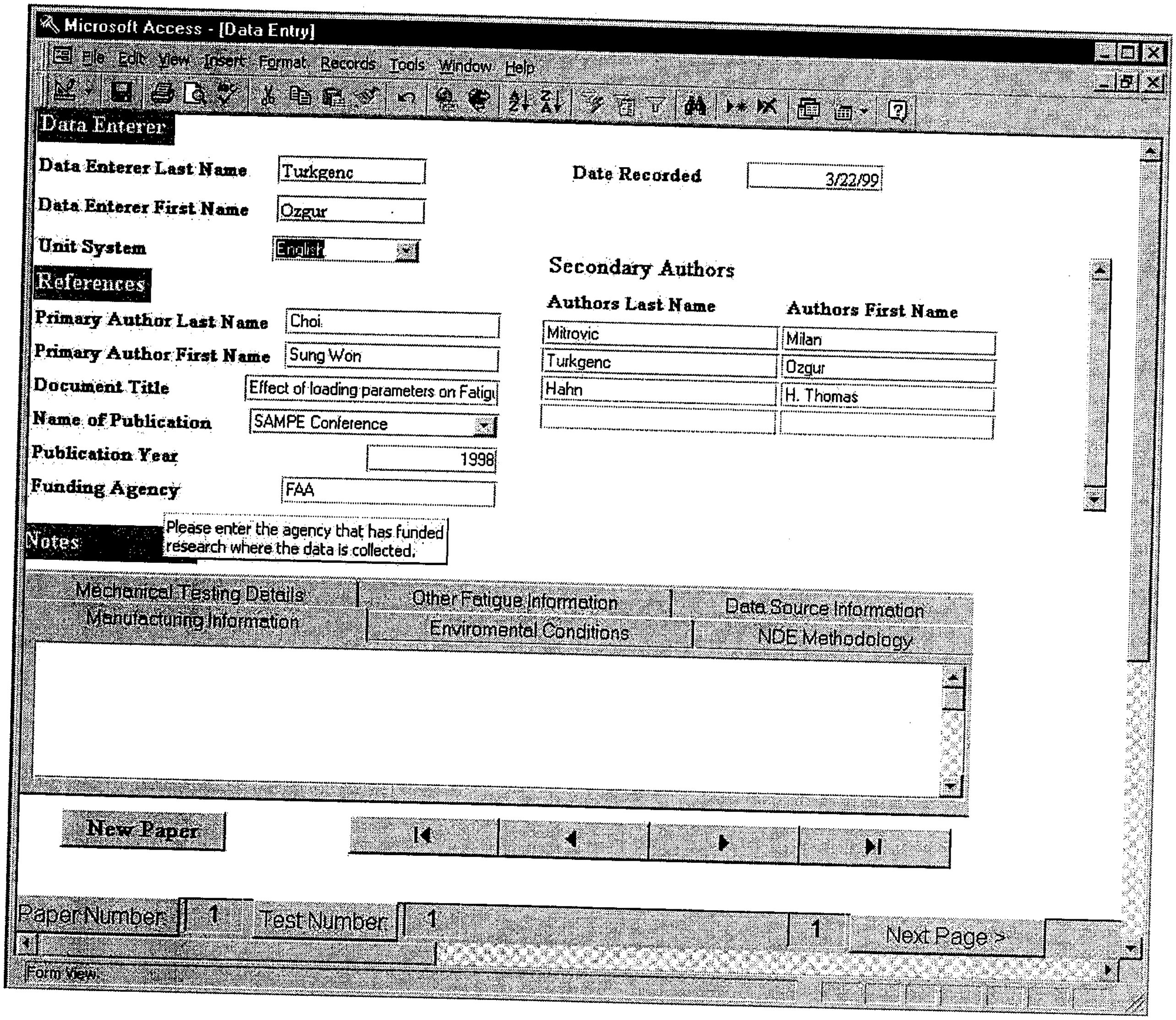


FIGURE 14. DATA ENTRY USER INTERFACE: PAGE 1

After a user has navigated to a particular publication (data source) in the first page, additional information may be entered or existing information modified on Page Two. This page contains tests and experimental results in nine cascaded folders for the publication selected in Page One and is based on the second tier of the database (figure 15). Within each folder, the user finds pertinent parameters and starts assigning values either by looking at and selecting previous entries or by typing in a new value. Most of the parameter fields contain pull-down menus enabling easy viewing of the previously entered values (figures 16, 17, 18, and 19). The pull-down menus are updated each time a new value is entered. As the user moves to a different test, contents of the nine folders are replaced with the data of the current test. Any time during data entry, the user can click on the Previous Page button, to go back to the first page. Once in the first page, the user can navigate to any other publication and repeat the above process for entering new or modifying existing data.

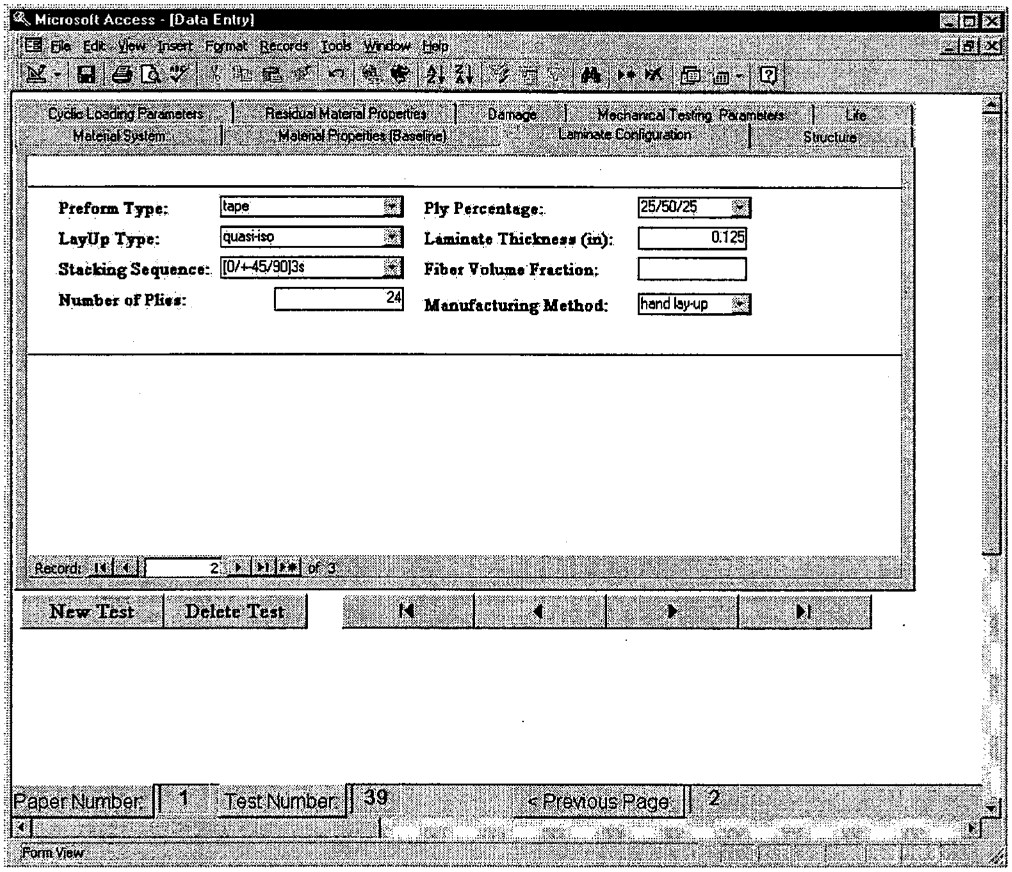


FIGURE 15. DATA ENTRY USER INTERFACE: PAGE 2

(a)

(b)

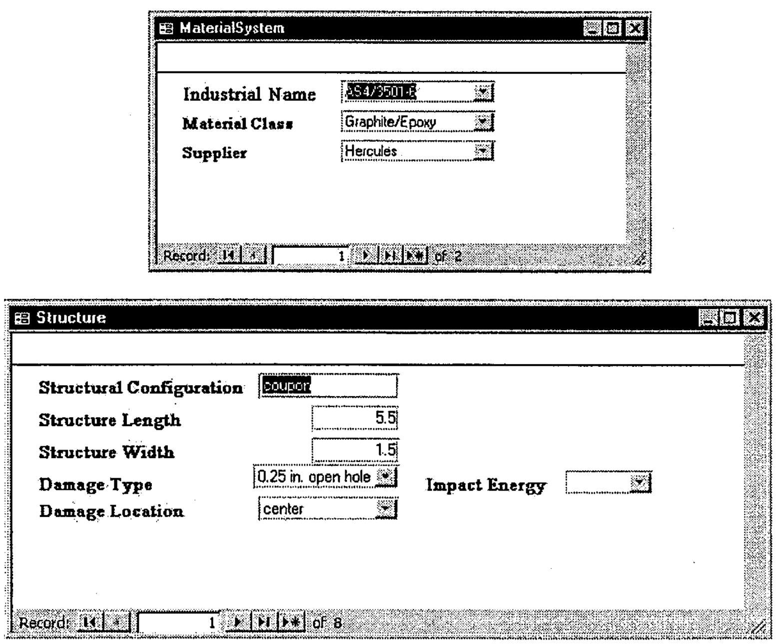


FIGURE 16. (a) MATERIAL SYSTEM AND (b) STRUCTURE TABLE FORMS

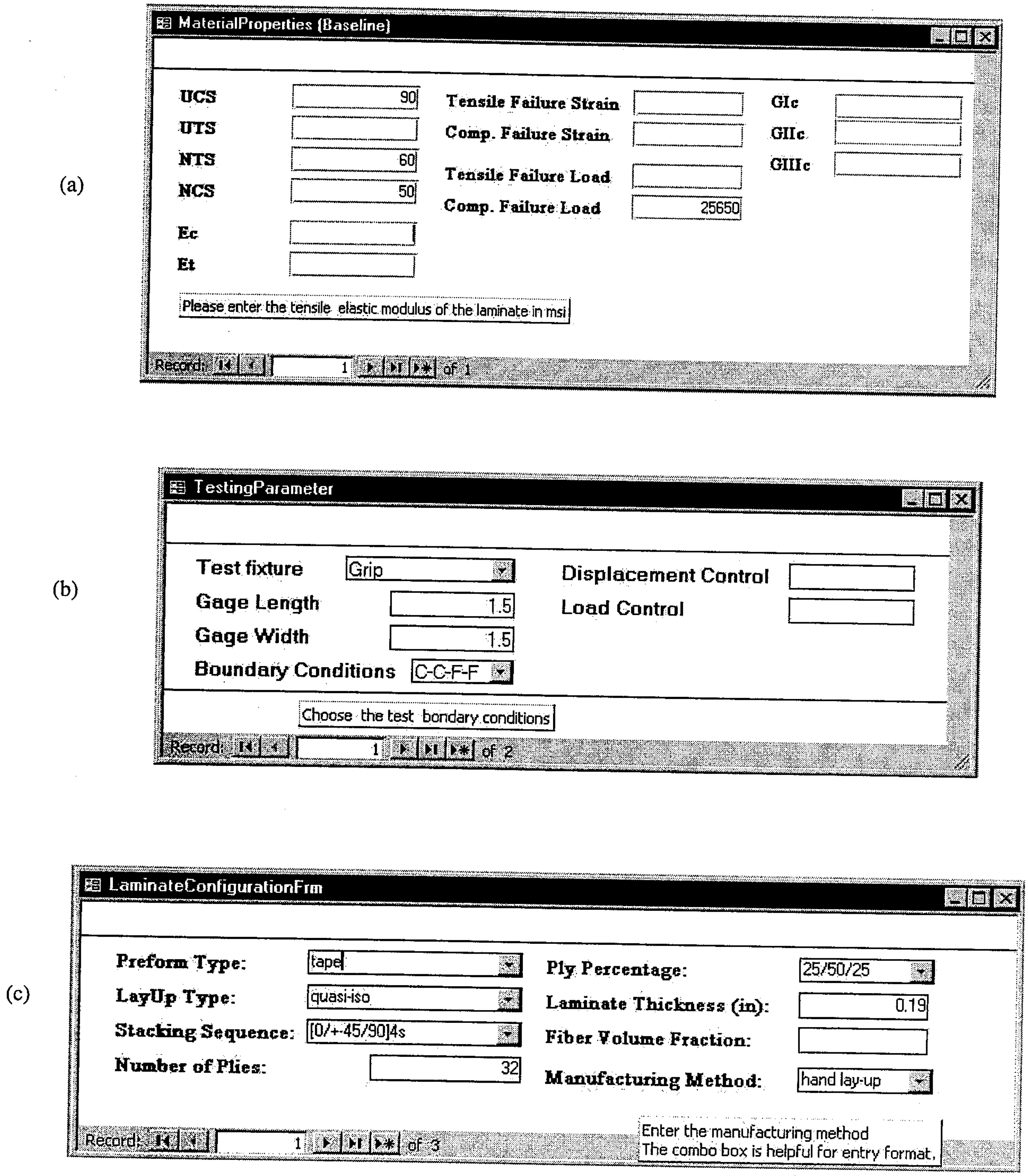


FIGURE 17. (a) MATERIAL PROPERTIES BASELINE, (b) TESTING PARAMETERS, AND (c) LAMINATE CONFIGURATION TABLE FORMS

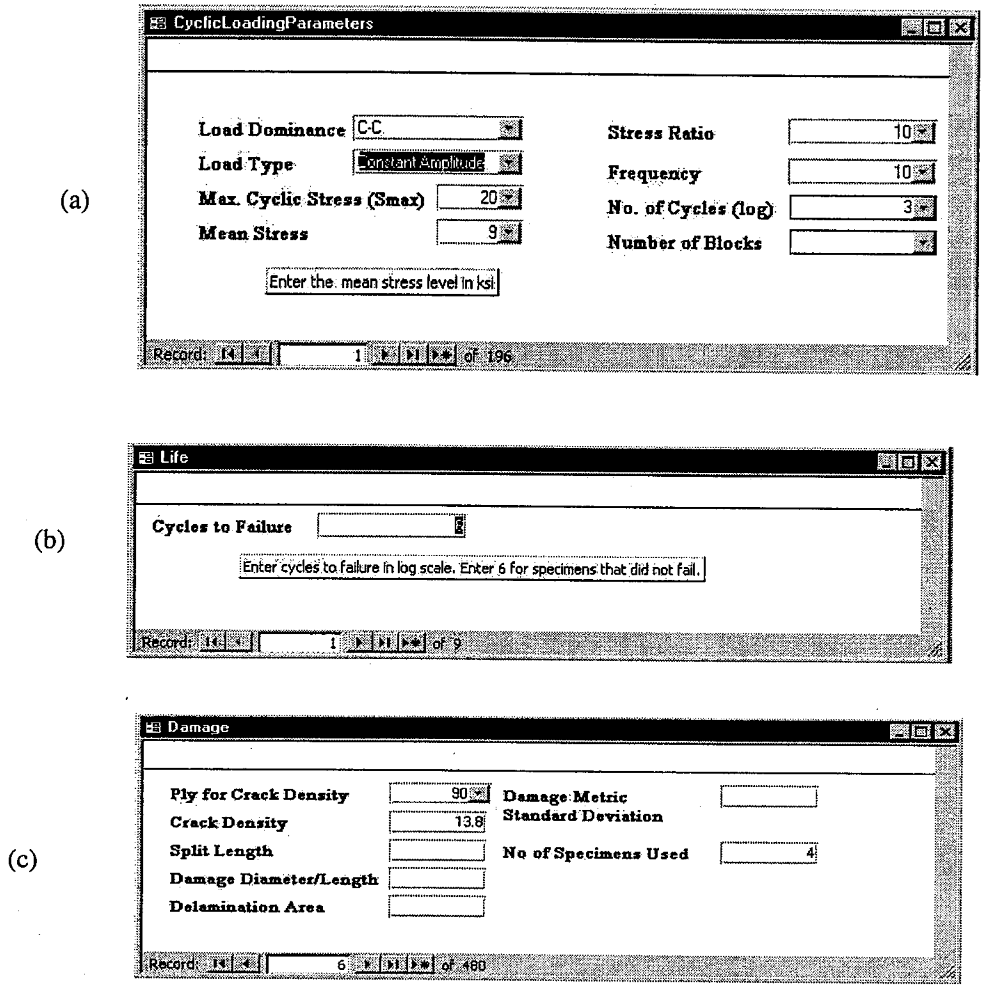


FIGURE 18. (a) CYCLIC LOADING PARAMETERS, (b) LIFE, AND (c) DAMAGE TABLE FORMS

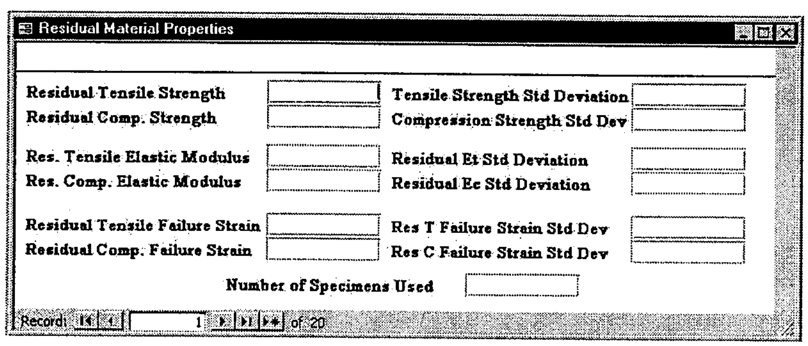


FIGURE 19. RESIDUAL MATERIAL PROPERTIES TABLE FORMS

A few data entry and representation conventions had to be developed for *Durability* as follows. For "Maximum Stress Level" (S_{max}), the absolute value of the maximum stress is entered. Since there is another field called "Load Dominance" that allows the user to indicate if fatigue loading is tensile or compressive, and there is also the "Stress Ratio" (R) field, negative values for S_{max} need not be indicated. One other data entry convention applied is the indication of no fatigue failure by entering 10^6 for Cycles to Failure (N). As a result, fatigue information in *Durability* is limited to one million cycles. It should also be noted that Compression Failure Load and Tension Failure Load in Baseline Material Properties are for a plain laminate without any stress raisers or damage. Finally in Stress Ratio, $R = \infty$ is represented by $R = 10,000$ since Stress Ratio field only accepts numeric values.

5.2.2 Data Retrieval Interface.

The Data Retrieval interface allows the user to query the database for desired information. The data retrieval form consists of two main parts: the top section of the form is designed for building the search string for information and the bottom section for presenting the results of the search (figure 20).

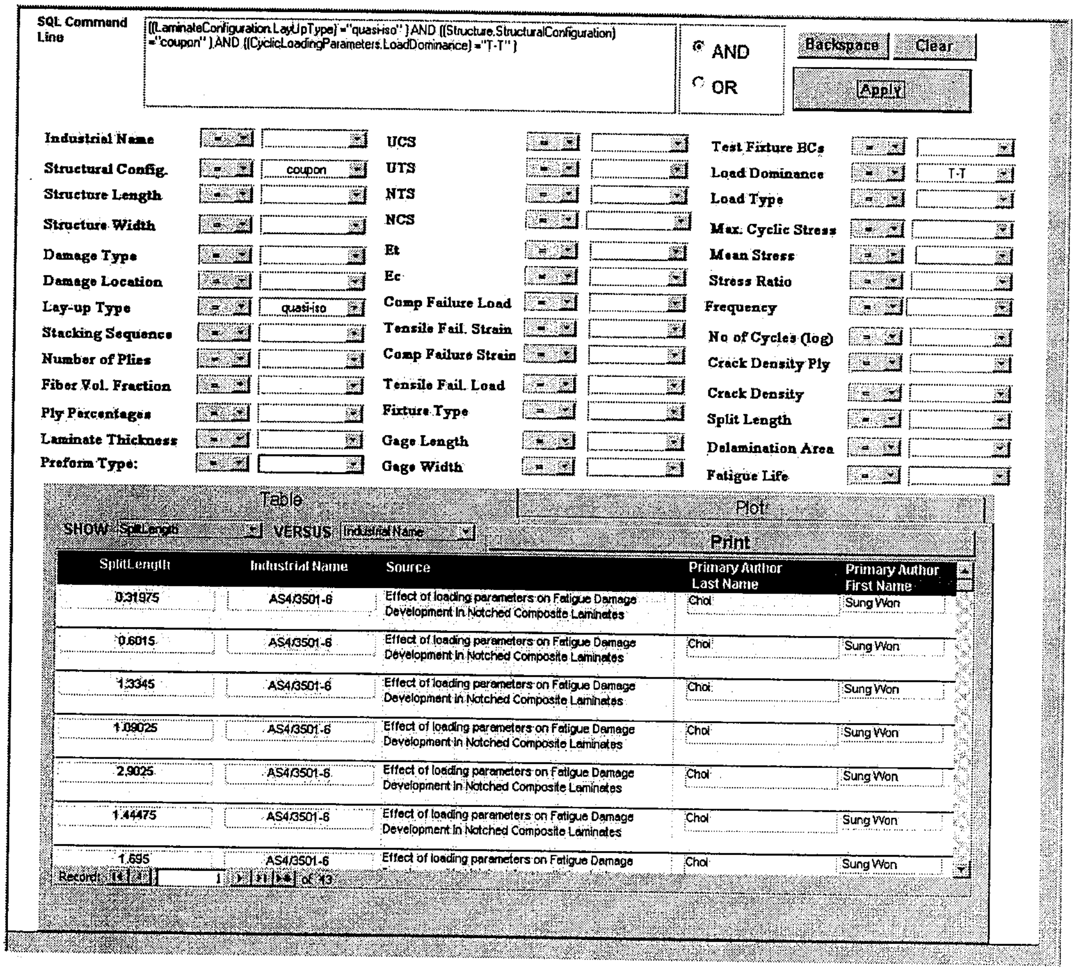


FIGURE 20. DATA RETRIEVAL INTERFACE WITH RESULTS TABLE

Implementation details for the Data Retrieval interface are discussed in section 4.2.2 where *DamTol* system is introduced. For *Durability*, different variables are used and selected from the existing fields within the database. Of the 79 data fields, 39 are available to be chosen by the user in the data retrieval process. As previously, some of the data fields include supporting data such as the number of specimens tested and standard deviation information on key parameters. Also, data source information and *Notes* fields are not applicable to parametric studies. Therefore, such fields are not available in the data retrieval process. The user can use the 39 specified fields to create a search string. These fields and a representative value for each field is presented in table 15.

TABLE 15. FIELDS AND EXAMPLE VALUES FOR DATA RETRIEVAL

Parameter	Field Name	Representative Value	Corresponding Table
Material System	Industrial Name	AS4/3501-6	MaterialSystem
Coupon/Panel/Subcomponent/Component	Structural Configuration	Panel	Structure
Length of structure	Structure Length	10 inches	Structure
Width of structure	Structure Width	5 inches	Structure
Plain/notched/impacted	Damage Type	0.25 in. open hole	Structure
Damage Location	Damage Location	center	Structure
Configuration of the laminate	Preform Type	tape	LaminateConfiguration
Lay-up type of composite	Lay-up Type	Quasi-iso	LaminateConfiguration
Stacking sequence of composite	Stacking Sequence	[0/45/-45/90]2S	LaminateConfiguration
No. of plies in the laminated composite	Number of Plies	16	LaminateConfiguration
Fiber volume fraction of composite	Fiber Volume Fraction	63	LaminateConfiguration
0/±45/90 %'s in the composite laminate	Ply Percentages	(25/50/25)	LaminateConfiguration
Thickness of the laminate	Laminate Thickness	0.080 inches	LaminateConfiguration
Unnotched compression strength	UCS	98 ksi	Material Properties Baseline
Unnotched tension strength	UTS		Material Properties Baseline
Notched Tension Strength	NTS		Material Properties Baseline
Notched Compression Strength	NCS		Material Properties Baseline
Elastic Modulus (tension)	Et		Material Properties Baseline
Elastic modulus (compression)	Ec	7.0 msi	Material Properties Baseline
Tensile Failure Strain	TensileFailureStrain		Material Properties Baseline
Compressive Failure strain	CompressiveFailureStrain	0.8%	Material Properties Baseline
Compressive Failure Load	CompressiveFailureLoad		
Tensile Failure load	TensileFailureLoad		Material Properties Baseline
Test fixture type	Fixture Type	Grip	TestingParameters
Mechanical test gage length	Gage Length	3 inches	TestingParameters
Gage width for compression test	Gage Width	1.5 inches	TestingParameters
Test fixture boundary conditions	Test Fixture BCs	C-C-F-F	TestingParameters
Dominance of cyclic loading (T-T, C-C)	Load Dominance	T-T	CyclicLoadingParameters
Type of cyclic loading (block, spectrum)	Load Type	Modified TWIST	CyclicLoadingParameters
Maximum cyclic stress level (in ksi)	Smax	25 ksi	CyclicLoadingParameters
Mean stress level (in ksi)	Smean	13.75 ksi	CyclicLoadingParameters
Stress Ratio (R)	Stress Ratio	10	CyclicLoadingParameters
Frequency of loading cycles (in Hz)	Frequency	10 Hz	CyclicLoadingParameters
Number of load cycles applied (in log)	No of Cycles	5	CyclicLoadingParameters
Ply for which crack density is indicated	CrackDensityPly	90	Damage
Ply crack density per unit width (in^{-1})	Crack Density	12 in^{-1}	Damage
Length of longest split in notched laminate	Split Length	0.5 in.	Damage
Area of delamination	Delamination Area	1.3 sq. in.	Damage
Total cycles to failure (in log)	Fatigue life	5.5346	Life

As the user chooses and assigns values to parameters by using the list of logical operators, a search string based on SQL is created automatically and the "APPLY" button triggers the program to find the record in the database that satisfies the search string. The results can be viewed either as a table or a graph. Similar to *DamTol*, two different chart types are used to handle both numeric vs. numeric and alphanumeric vs. numeric plots, called *X-Y Plot* and the *Bar Graph*, respectively. Within each option there are two pull-down menus that allow the user to choose the horizontal and the vertical axes of the graph with fields pertinent to fatigue design. As a result, the user is equipped with a tool that provides instant comparison of any two variables under any set of constraints (figure 21).

(a)

(b)

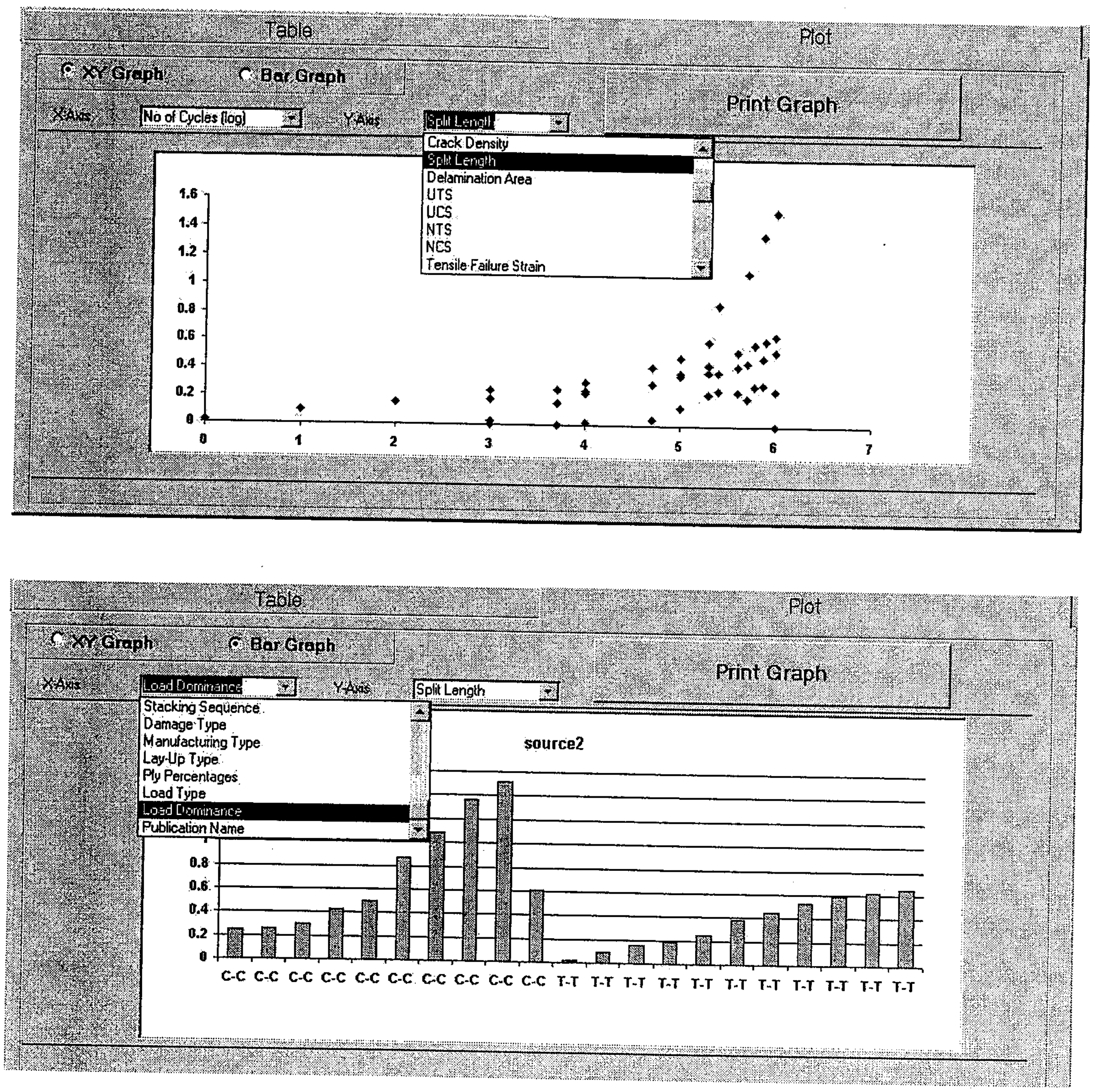


FIGURE 21. (a) X-Y PLOT RESULT INTERFACE WITHIN DATA RETRIEVAL AND (b) BAR GRAPH RESULT INTERFACE WITHIN DATA RETRIEVAL

In the table folder, results are presented in five columns. The first two columns correspond to the parameters that are chosen by the user. The third through fifth columns show information about the source documents from which the queried data is taken. An important feature of this section is that for any search result detailed information in the form of nine cascaded folders can be obtained simply by double clicking on the source document (figure 22).

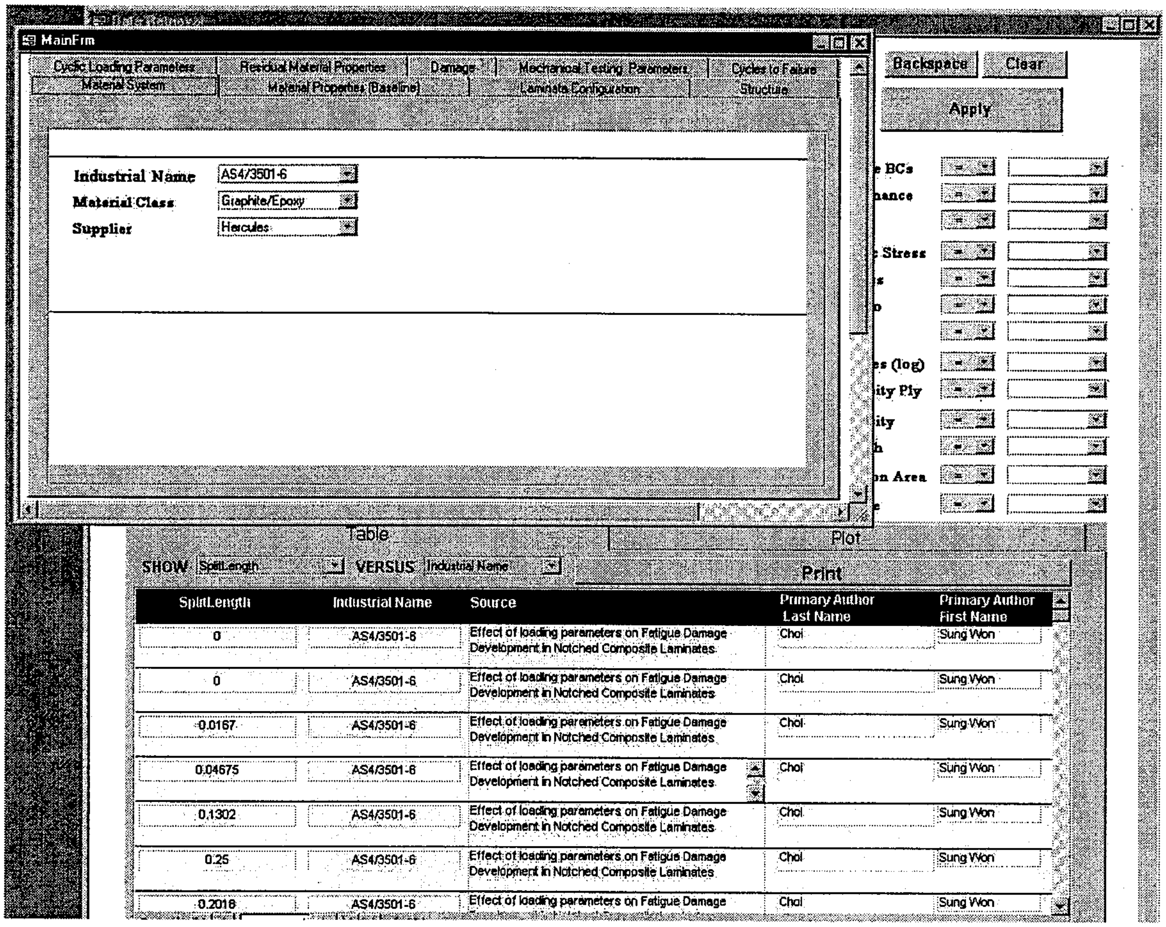


FIGURE 22. DATA RETRIEVAL RESULTS TABLE AND THE POP-UP WINDOW THAT PRESENTS ALL PARAMETER VALUES BEHIND THE SELECTED RESULT

5.2.3 Expert Solution Interface.

The third interface in the *Durability* switchboard is intended to assist the user when none of the stored records can exactly satisfy the requirements imposed. The Expert Solution compares the user's required values with that of experimental data stored in the database and arrives at conclusions by using the embedded reasoning mechanism described in section 4.2.3. Data processing methodology and the reasoning mechanism is identical to *DamTol*'s Expert Solution interface. Thirty four of the parameters listed in table 15 were employed for Expert Solution input process. Using pull-down menus, the user specifies input values by selecting the best matching value that exists in a list of all values stored in the database for that parameter, as shown in figure 23.

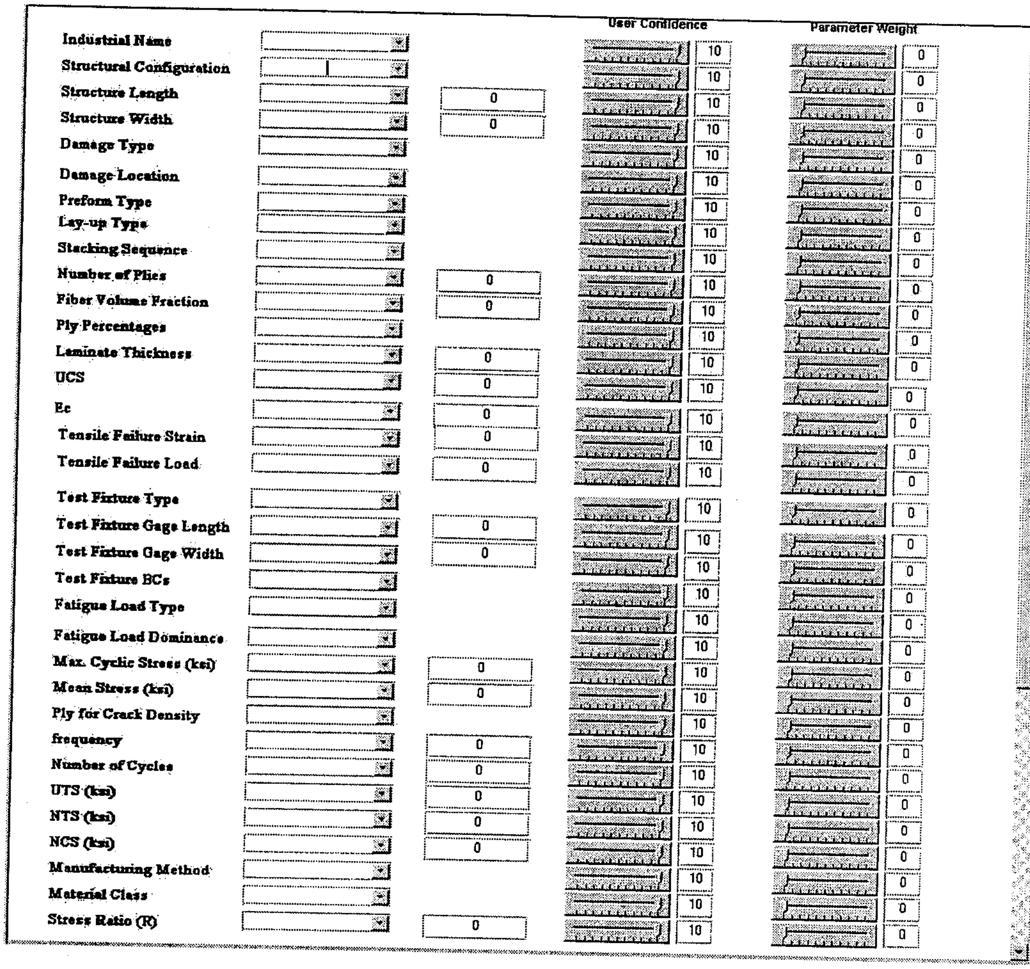


FIGURE 23. EXPERT SOLUTION INTERFACE: INPUT PARAMETERS

Results presented are Residual Tensile Strength, Residual Compression Strength, Delamination Area, and Split Length for selected number datasets in the database that are most similar to the user's composite design ranked according to their calculated total confidence values (figure 24). Overall confidence levels can be plotted versus any of the output parameters listed above by using the Plot capability generated for this interface.

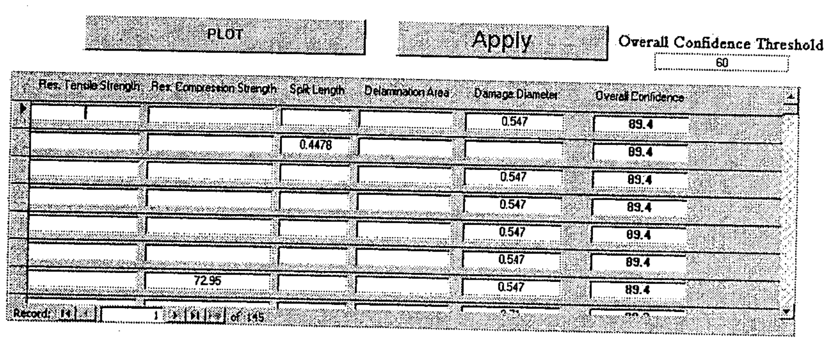


FIGURE 24. RESULTS DISPLAYED WITHIN EXPERT SOLUTION AFTER INPUT VALUE AND CONFIDENCE THRESHOLD SELECTION

6. EXAMPLES.

6.1 *DamTol* EXAMPLES.

Two examples of parametric studies and two cases of similarity studies are presented to demonstrate the practical use and capabilities of *DamTol*. Parametric study cases are conducted using the Data Retrieval interface and the similarity study cases are conducted using the Expert Solution interface. Both examples are picked from issues that were addressed by previous research studies and practical design efforts.

6.1.1 Compression Strength after Impact Data Analysis.

The asymptotic behavior of compression strength after impact as a function of impact energy per unit thickness has been demonstrated and discussed in reference 3. Impact energy has also been identified as the strongest parameter affecting the impact damage tolerance behavior of composites [22, 48]. Therefore, it is important to establish the impact energy dependence of residual properties for a composite structure with certain material system.

For the CSAI analysis, a material system was chosen, laminate thickness values were constrained by the number of plies, and by a coupon size structure impacted at its center. Table 16 shows the input parameters and the SQL line generated by *DamTol*. An impact energy versus CSAI plot shows the monotonic decrease in CSAI as energy values increase (figure 25). This plot exhibits the typical behavior observed for composite structures, where CSAI reaches a threshold value as impact energy reaches higher values.

TABLE 16. FIXED PARAMETERS FOR CASE 6.1.1

Parameter	Value
Number of Plies	32
Structural Configuration	"Coupon specimen"
Material System (Ind. Name)	"AS4/3501-6"
Impact Location	"center"
Preform Type	"laminated prepreg"
((LaminateConfiguration.PreformType)= "laminated prepreg") AND ((LaminateConfiguration.numberofplies)=32) AND ((MaterialSystem.IndustrialName) = "AS4/3501-6") AND ((Structure.StructuralConfiguration) = "coupon specimen") AND ((ImpactParameters.ImpactLocation) ="center")	

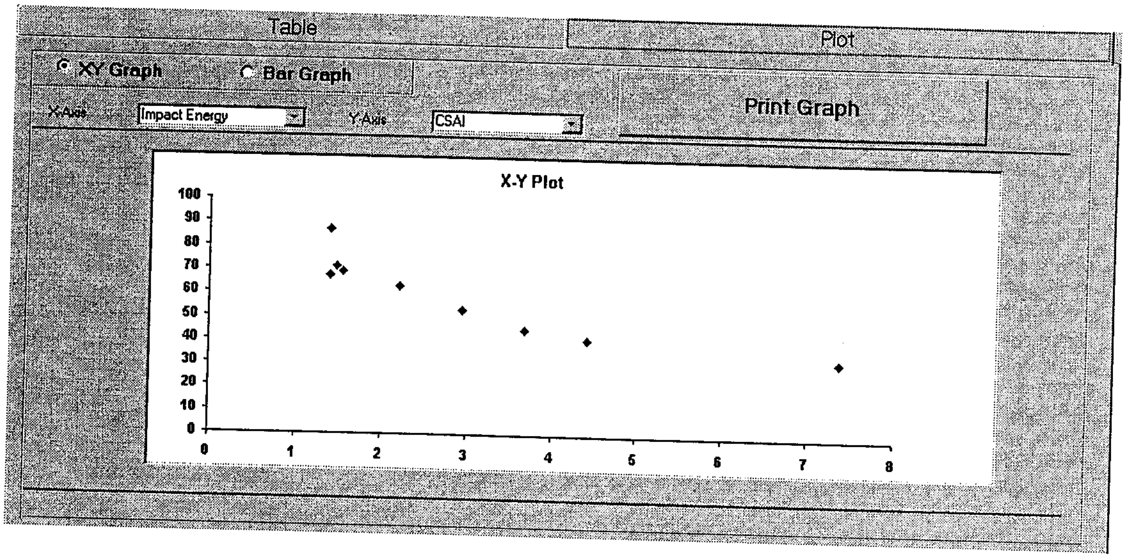


FIGURE 25. IMPACT ENERGY (ft-lb) VERSUS CSAI (ksi) GRAPH UNDER THE SPECIFIED PARAMETERS OF CASE 6.1.1

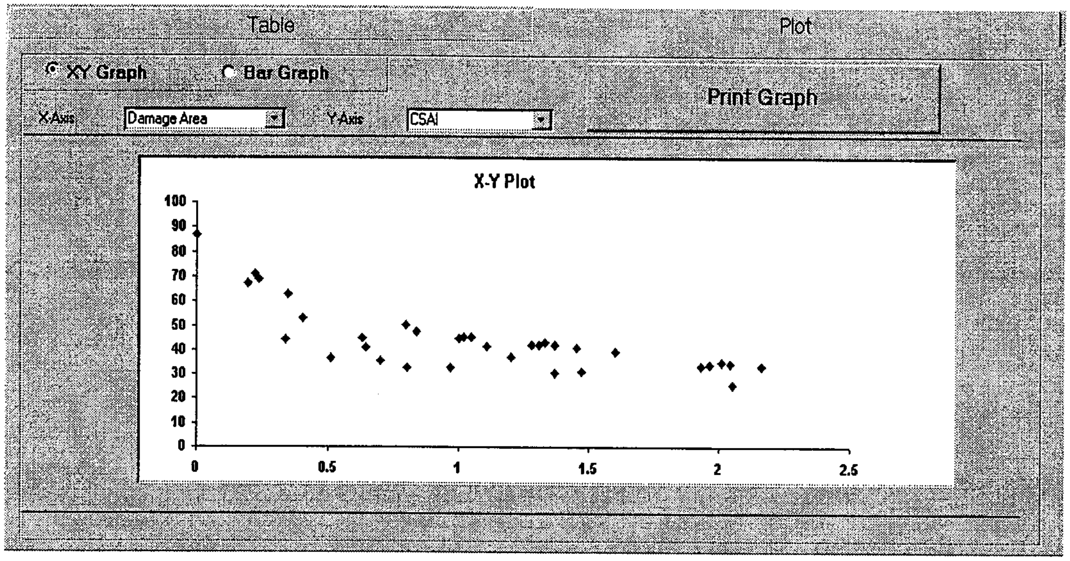
6.1.2 Damage Area vs Compression Strength After Impact Data.

It has also been reported that CSAI exhibits asymptotic behavior as damage area increases [49, 50]. This case is an attempt to capture this type of behavior. Input parameters and their values are given in table 17. It can be seen from figure 26(a) that under the given constraints, as damage area reaches large values, the CSAI level reaches a threshold. Figure 26(b) presents the stacking sequence dependence of CSAI for the same input values. It should be noted that these values are for structures with less than 2.5 sq. in. damage area. The trend of CSAI is not clear with different stacking sequences.

TABLE 17. FIXED PARAMETERS FOR CASE 6.1.2

Parameter	Value
Structural Configuration	"coupon specimen"
Width of Structure	< 3.0 inches
Structure Type	"flat coupon"
Material System (Ind. Name)	"AS4/3501-6"
((Structure.StructuralConfiguration) ="coupon specimen") AND ((Structure.StructureType) ="flat coupon") AND ((MaterialSystem.IndustrialName) = "AS4/3501-6") AND ((Structure.W) <3)	

(a)



(b)

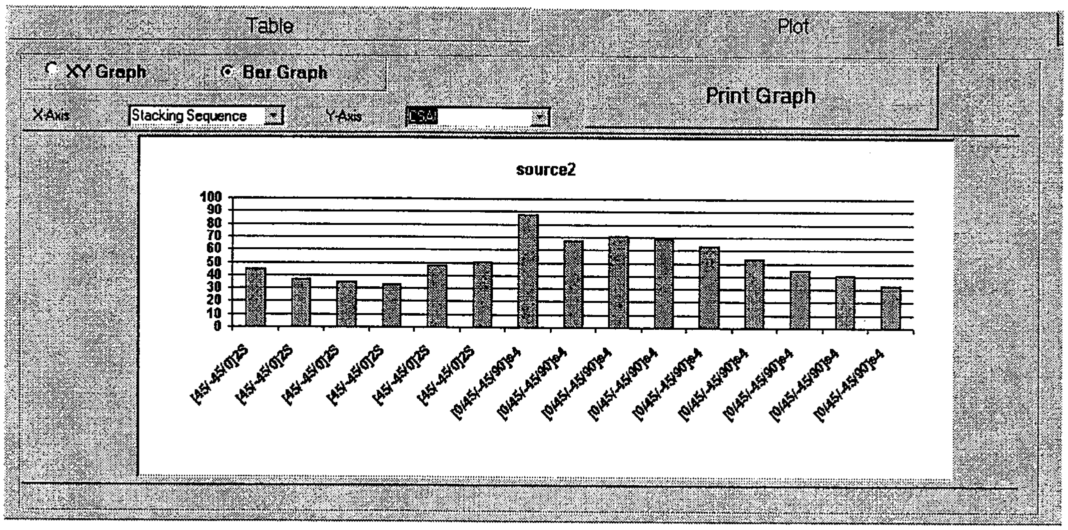


FIGURE 26. UNDER THE SPECIFIED PARAMETERS OF CASE 6.1.2 (a) DAMAGE AREA (in^2) VERSUS CSAI (ksi) AND (b) STACKING SEQUENCE VERSUS CSAI (ksi)

6.1.3 Similarity Analysis for a Generic Composite Structure.

A set of composite design data was entered using the fields of the Expert Solution option (table 18). The set of data was chosen for a particular material system, structural configuration, and impact parameters often encountered in airborne composite structures. Two different runs were performed by changing preform type value from tape to stitched while all other entries were the same. The results of the two cases are presented in figure 27. The highest overall confidence calculated for the laminated (taped) composite case is 88.3% for a CSAI equal to 16.5 ksi. For the stitched case, the CSAI value is much higher being equal to 42.9 ksi with a slightly lower overall confidence level of 80.8% because the stitched data sets match user's requirements less often. These results agree with the fact that stitching is effective in improving impact damage tolerance performance.

TABLE 18. INPUT VALUES FOR CASE 6.1.3

Parameter	Value	User Confidence	Weight
Material System (Ind Name)	AS4/3501-6	10	5
Structure Length (in.)	10 inches	10	5
Structure Width (in.)	10 inches	10	5
Preform Type	Tape/Stitched	10	10
Lay-up Type	Quasi-iso	8	5
Number of Plies	48 ± 8	8	5
Compression Fixture	NASA ST-1	9	5
Impact Type	Drop Weight	8	5
Impact Fixture	NASA	9	5
Impact Energy	100 ± 10 ft-lb	10	10

PLOT Apply

(a)

CSAI	Damage Area	Dent Depth	Overall Confidence
16.5	16	0.1	88.3
18	18		81.7
20.23	18		81.7
16.62	26.29	0.1	80.0
20.04	21.43		73.3
16.92	23.41		65.8
15.16	1	0.0468	65.0

PLOT Apply

(b)

CSAI	Damage Area	Dent Depth	Overall Confidence
42.9		0.17	80.8
66.3		0.03	74.2
59.6		0.03	74.2
50.3		0.05	74.2
53.75		0	71.7
16.5	16	0.1	71.7
56.7		0	71.7

FIGURE 27. IN CASE 6.1.3, RESULTS OF EXPERT SOLUTION FOR (a) TAPE COMPOSITE AND (b) STITCHED COMPOSITE

With the given input numbers in table 18, highest possible overall confidence is 93.3%. With stitched/unstitched condition being not satisfied and all other requirements satisfied it is 76.6%. One of the unstitched data sets slips into the output in figure 27(b) because it satisfied almost all of the other requirements. The user can also conduct a more crude analysis by having only a few requirements where the effect of satisfying each requirement is greater. It should be noted that as the number of specified fields increases, the sensitivity of the overall confidences of the reported values decreases.

6.1.4 Optimum Selection for a Composite Structure With a New Material System.

If a new material system is to be used in the design of a composite structure, it may be difficult to find available data for the impact behavior of that material system. One way of starting the data search is to compare the known properties of the new material system to ones that were used before in structures with similar dimensions and geometry under similar loading. If this comparison results in good agreement between the new material system and the ones with available impact behavior data, then the impact behavior of the new structure and consequently its postimpact performance can be expected to be similar to the values obtained form existing structures.

Table 19 shows the input design data for a case where a new material system is used. A 10 x 5 inch laminated composite flat plate impacted at its center with an impact energy of 100 ft-lb is used. The elastic modulus of the new material system is known to be 7.6 msi. The testing condition is chosen to be the same as the NASA ST-1 standard used in reference 51.

TABLE 19. INPUT VALUES FOR CASE 6.1.4

Parameter	Value	Range	C_i	W_i
Compression Fixture	NASA ST-1		10	2
Elastic Modulus, E_c	7.6	2.5	8	10
Structural Configuration	Coupon		7	2
Structure Length (in.)	10	3	10	5
Structure Width (in.)	5	3	10	5
Impact Energy (ft-lb)	100	5	9	10
Structure Type	Flat plate		10	5
Impact Location	Center		10	2
Preform Type	Tape prepreg		10	8

When the user starts to specify the values for the new material system, the individual uses the pull-down menus to pick the best matching value for each parameter. If the exact value is not in the menu then the best matching value should be chosen and a lower confidence value assigned. For example, in the case of structural dimensions, the values of 10 in. and 5 in. for length and width respectively were found on the list and therefore a confidence value of 10 was entered for both values. A parameter weight of 5 was picked due to the lesser effect of these parameters on the postimpact behavior when compared to other parameters considered. Other values are entered in a similar fashion and the case was analyzed.

Some of the results are presented in table 20. The highest overall confidence calculated for the case is 76.7% for CSAI values ranging between 16.92 and 20.23 ksi (figure 28). The actual values for the specified parameters of the presented results are also included in table 20. Looking at the results, it can be deduced that mechanical performance of the new material system may be similar to that of AS4/3501-6 or IM6/CYCOM. Results are also reported for AS4/3502 composite coupons with somewhat lower confidence at very low impact energy rates, but a other data for these records show that the thickness of the laminate is much less than that of other results. This indicates that initially not all pertinent parameters were selected and it pays to go back to investigate nonconforming data. The supporting data is reached by clicking the line of the result in question to bring up the data fields window.

6.2 *Durability* EXAMPLES.

In this section, four examples of data retrieval and one example of a similarity study are presented. The examples were chosen to demonstrate how *Durability* can be used in data synthesis. Also, the examples attempt to show the advantages of using this system in capturing fatigue behavior information.

6.2.1 Crack Density Growth for Plain Specimens Under Constant Amplitude Loading.

In this example [2], the effect of loading type on the crack density growth in coupon specimens is investigated. The coupons are plain having no initially induced damage or other types of stress raisers. The crack density growth trends are compared for the -45 degree plies of the laminate under constant amplitude T-T and T-C loading for a maximum load level of 40 ksi, which corresponds to 40% of the ultimate tensile strength (UTS). Hence, load dominance parameter is not specified in the input. The input parameters are listed in table 21.

From the results, it is apparent that under T-C loading, cracks initiate at a lower number of cycles and increase at a faster rate (figure 29). The input parameters can be changed to investigate the stress range under different maximum load levels. If the load dominance value were specified to be either T-T or T-C, then only one set of points would be visible in the plot.

6.2.2 Comparison of Damage Under Full and Modified TWIST Spectrum Loading.

Fatigue spectrum tests are conducted to better simulate the in-service loading conditions that aerospace structures may encounter. Modifying spectrum tests by the deletion of the lowest load levels in order to shorten the testing time is considered as an option to reduce testing time. In this example, comparison is sought for full and modified TWIST spectrum loading [52] at a mean stress level of -15 ksi. Composite coupon specimens containing a 0.25-in-diameter open hole at the center are specified in the input parameters. A list of input parameters and the SQL command line generated by he system are given in table 22.

TABLE 20. RESULTS OF CASE 6.1.4

Overall Confidence	76.73	76.73	76.73	76.73	58.37	58.37	58.37	54.29	51.02	51.02
CSAI	18	20.23	16.92	20.04	16.5	15.16	16.62	16.2	20.2	20.7
Compression Fixture	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1	NASA ST-1
Elastic ModulusEc	(Not Reported)								18.5	18.5
Structural Configuration.	Coupon	Coupon	Coupon	Coupon	Coupon	Coupon	Coupon	Coupon	Coupon	Coupon
Structure Length	10	10	10	10	10	10	10	10	10	10
Structure Width	7	7	7	7	7	7	7	7	3	3
Impact Energy	100.14	100.16	100.51	100.39	91.32	9.1	9.15	20.6	1.02	3.11
Structure Type	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate
Material System	AS4/3501-6	AS4/3501-6	AS4/3501-6	AS4/3501-6	AS4/3501-6	AS4/3501-6	IM6/CYCOM	AS4/3501-6	AS4/3502	AS4/3502
Impact Location	Center	Center	Center	Center	Center	Center	Center	Center	Center	Center
Preform Type	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg	Tape prepreg

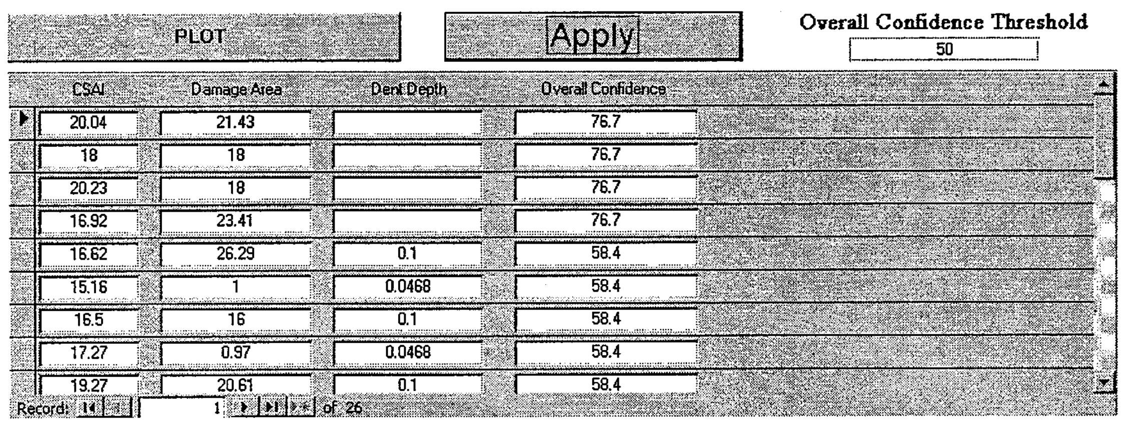


FIGURE 28. RESULTS OF EXPERT SOLUTION FOR LAMINATED COMPOSITE FLAT PLATE WITH SPECIFIED PARAMETERS IN CASE 6.1.4

TABLE 21. SPECIFIED INPUT VALUES AND THE SQL COMMAND LINE FOR CASE 6.2.1

Parameter	Value
Load Type	"constant amplitude"
Damage Type	"plain"
Crack Density Ply	-45
Maximum Cyclic Stress	40 ksi
((Structure.DamageType) ="plain") AND ((CyclicLoadingParameters.LoadType) ="Constant Amplitude") AND ((Damage.PlyforCrackDensity) =-45) AND ((CyclicLoadingParameters.Smax) =40)	

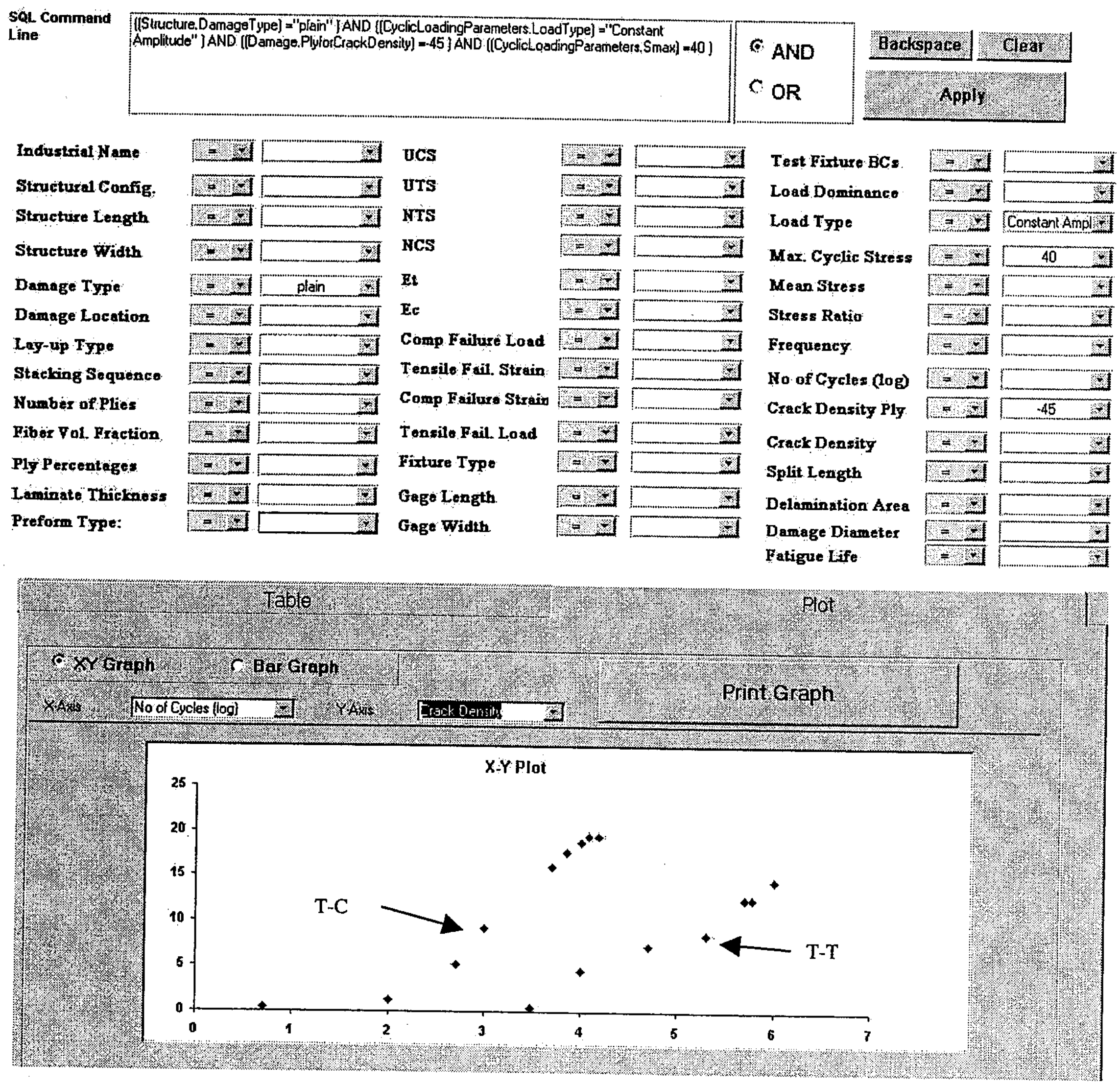


FIGURE 29. USE OF DATA RETRIEVAL INTERFACE TO INVESTIGATE THE EFFECTS OF T-T AND T-C LOADING ON THE COUPON SPECIMENS

TABLE 22. SPECIFIED INPUT VALUES AND THE SQL COMMAND LINE FOR CASE 6.2.2

Parameter	Value
Load Dominance	"compression"
Damage Type	"0.25 in. open hole"
Damage Location	"center"
Preform Type	"tape"
Mean Stress	-15 ksi
((Structure.DamageLocation) ="center") AND ((Structure.DamageType) ="0.25 in. open hole") AND ((LaminateConfiguration.PreformType) ="tape") AND ((CyclicLoadingParameters.Smean) = -15) AND ((CyclicLoadingParameters.LoadDominance) ="Compression")	

When the number of cycles is plotted against the split length growth for modified and full compression dominated TWIST spectrum fatigue loading, the split length does not change significantly with the shortened version of TWIST (figure 30). The Split length becomes nonzero at lower cycles in the modified TWIST. However, if the values are plotted for number of blocks rather than for number cycles, the data points coalesce (figure 31). Thus, the effect of deleting low level cycles from the fatigue spectrum is not significant for split length growth in composite coupons with an open hole.

6.2.3 Residual Compressive Strength of Impacted Composite Coupons Under Fatigue Loading.

From the damage tolerance point of view, an impact event is considered to be the most detrimental damage type in composites, as described in section 2. In some references, it is reported that long-term fatigue loading after impact does not cause a substantial decrease in residual strength [53]. This example examines residual compressive strength (RCS) data coming from a set of experimental results with various types of fatigue loading applied at different levels. The only input parameter specified is the damage type. Impact is chosen from the pull-down menu. Therefore, figure 32 shows RCS values collected under a variety of loading conditions. It should be noted that all of the impacted specimen data in the database come from the same data source and this can easily be verified using the Table of Data Retrieval interface. Hence the static compression strength after impact (CAI) value is the same for all fatigued specimens considered in this case. The CAI and the ultimate compression strength (UCS) values can be retrieved from the pop-out cascaded folders that are activated by selecting one of the results in the table interface. These values are 68.87 ksi and 90.0 ksi, respectively.

From figure 32, it is apparent if one considers scatter, that the residual strength degradation effect of fatigue, in general, is not at a comparable level to the strength reduction caused by the impact event itself. In that case the reduction in strength is from 90 ksi to 68.87 ksi. In some cases, the reported residual strength is even slightly greater than the CAI (68.87 ksi) value. Although the effect of fatigue loading may not be great on the residual strength, this is not the case for damage growth.

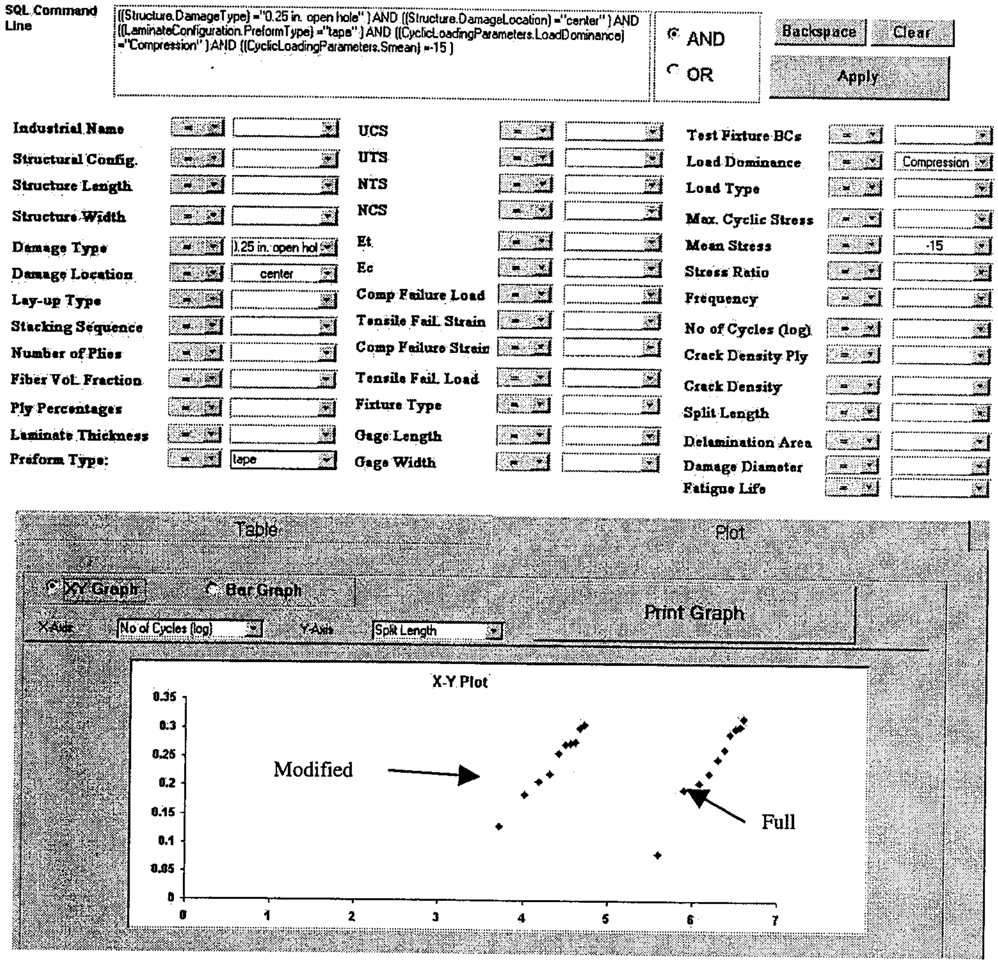


FIGURE 30. COMPARISON OF GROWTH IN SPLIT LENGTH DAMAGE METRIC UNDER FULL AND MODIFIED TWIST FATIGURE LOADING SPECTRUM

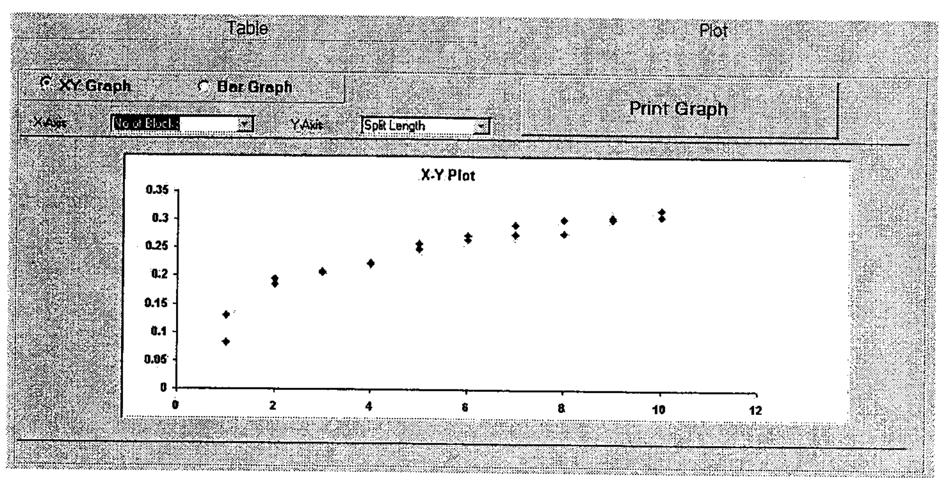


FIGURE 31. NUMBER OF BLOCKS VS SPLIT LENGTH FOR THE SPECIFIED INPUTS IN CASE 6.2.2

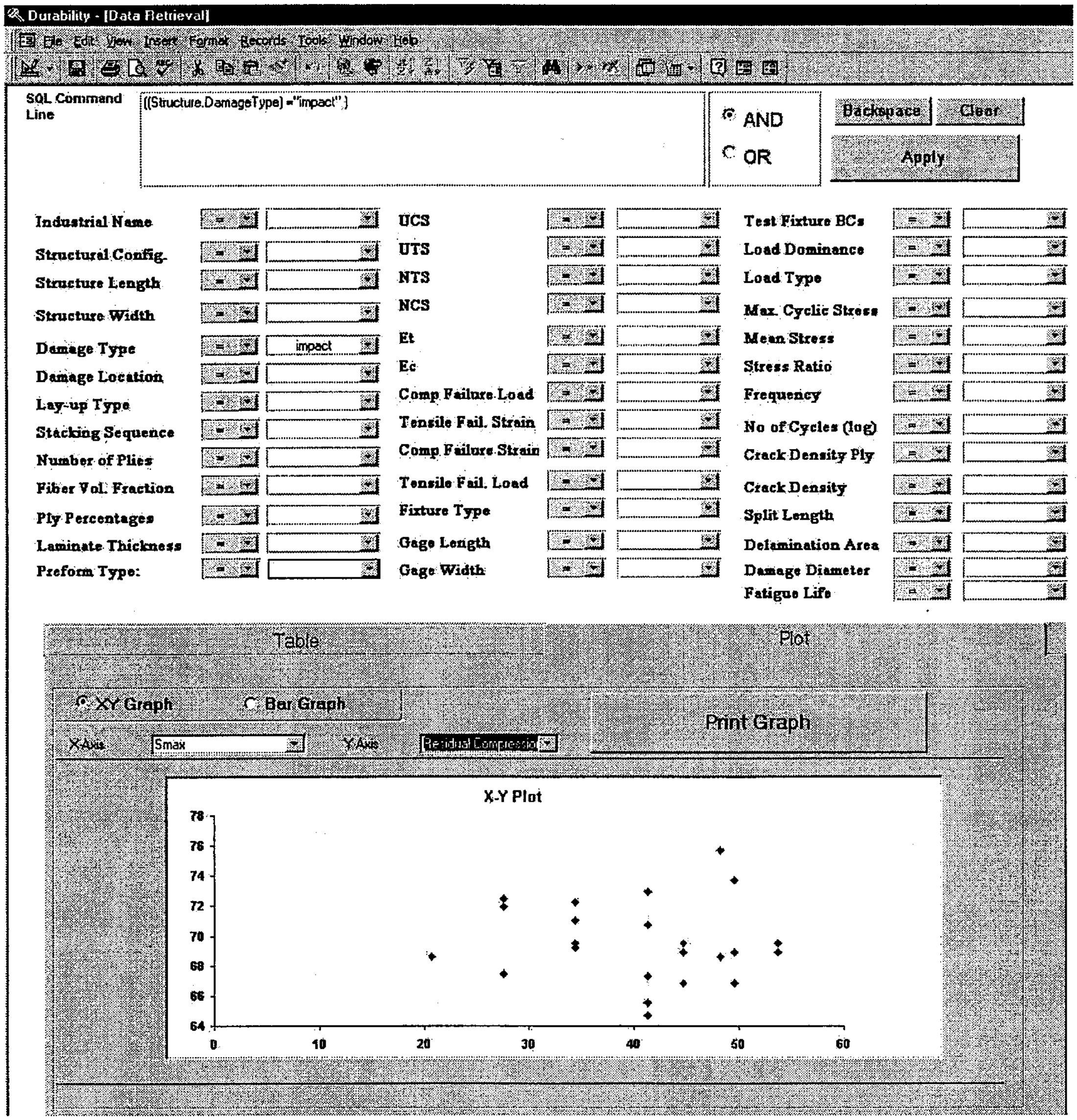


FIGURE 32. RESIDUAL COMPRESSION STRENGTH VALUES IN ksi FOR ALL IMPACTED SPECIMENS DATA IN *Durability*

Figure 33 shows number of cycles in log scale versus damage diameter in inches for compression dominated block loading of impacted composite coupons from the same set of test results. By using the X-Y Plot and the Table interfaces, it can be seen that the block loading consists of a high load level of -48.22 ksi followed by a low load level. Data presented comes from blocks containing the same high load and four different lower load levels. The stress ratio, R, is ∞, i.e., the specimens are cycled from no load to a maximum compressive load level. It should be noted that $R = \infty$ is represented by $R = 10{,}000$ in Durability as described in section 5.2.1. The four distinct growth trends presented in figure 33 correspond to four different lower loads succeeding the high level load. From the graph, it is evident that damage diameter grows under postimpact cyclic loading.

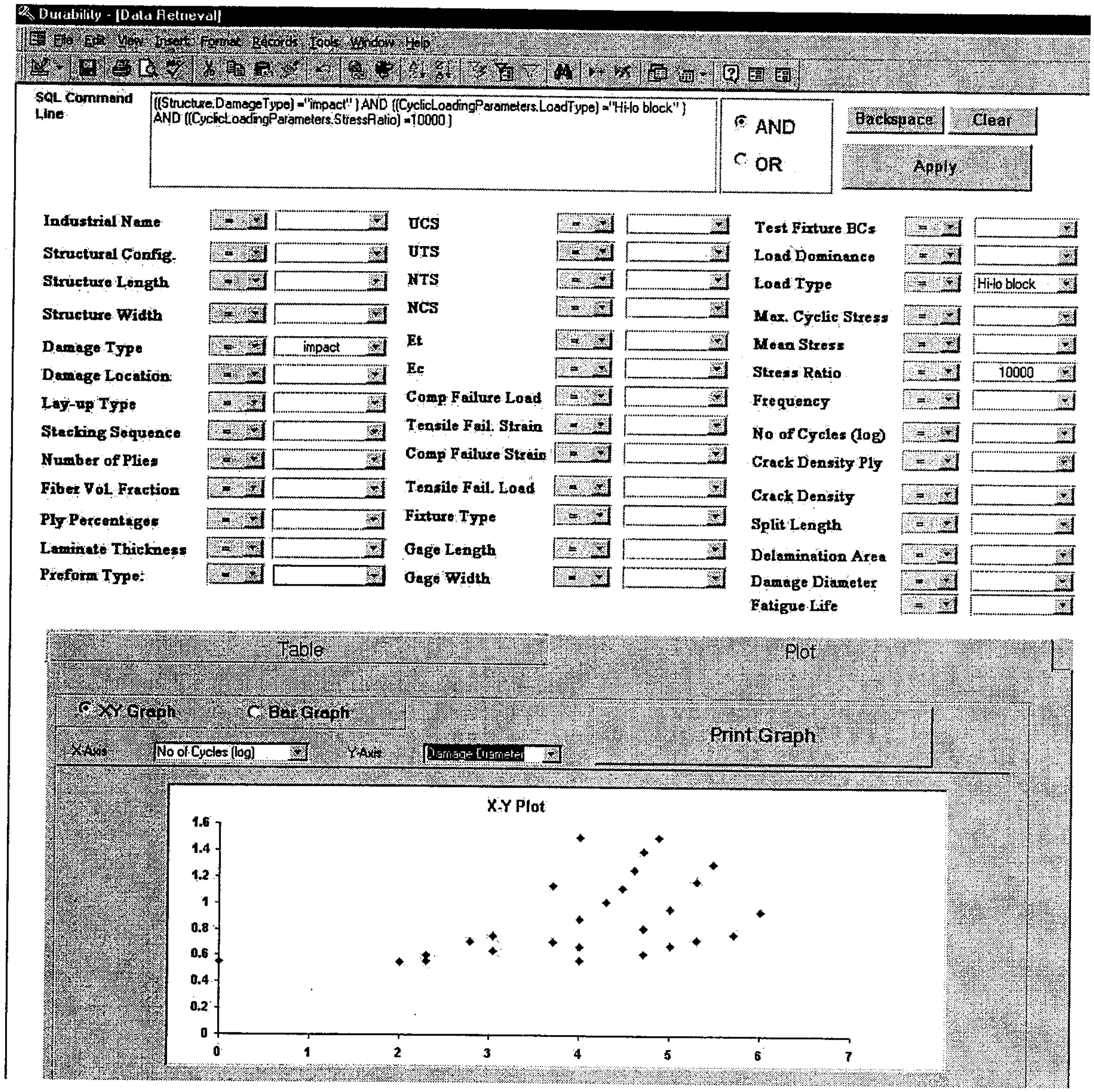


FIGURE 33. NUMBER OF CYCLES (LOG) VS DAMAGE DIAMETER FOR IMPACTED SPECIMENS UNDER COMPRESSION DOMINATED BLOCK LOADING

6.2.4 Cycles to Failure Information for Impacted and Open-Hole Specimens.

Fatigue life assessments are generally made using S-N type behavior where the number of cycles to failure is used as the life metric. Composite S-N behavior is different from metal behavior; composites have a flatter S-N curve with higher material variability. Nevertheless, S-N curves are commonly used to describe fatigue behavior in both composites and metals. This example compares the number of cycles to failure for impacted and open-hole composite coupons. To retrieve data for both impact and open-hole damage types, the OR link is used in query building. Specified input parameters and the full query line are presented in table 23.

TABLE 23. SPECIFIED INPUT PARAMETERS AND THE QUERY LINE GENERATED BY THE DATA RETRIEVAL INTERFACE FOR CASE 6.2.4

Parameter	Value
Load Dominance	"C-C"
Load Type	"Constant Amplitude"
Damage Type	"impact" OR "0.25 in. open hole"
Damage Location	"center"
Preform Type	"tape"
Maximum Stress Level	>30ksi
((Structure.DamageLocation) ="center") AND (((Structure.DamageType) ="0.25 in. open hole") OR ((Structure.DamageType) ="impact")) AND ((LaminateConfiguration.PreformType) ="tape") AND ((CyclicLoadingParameters.Smax) >30) AND ((CyclicLoadingParameters.LoadDominance) ="C-C") AND ((CyclicLoadingParameters.LoadType) ="Constant Amplitude")	

Querying results are shown in figure 34 by data points that form two flat S-N curves. From the combined output it is not clear which is more critical in fatigue. However, if the queries are run individually for impact and open-hole conditions, then each S-N curve can be seen (figure 35).

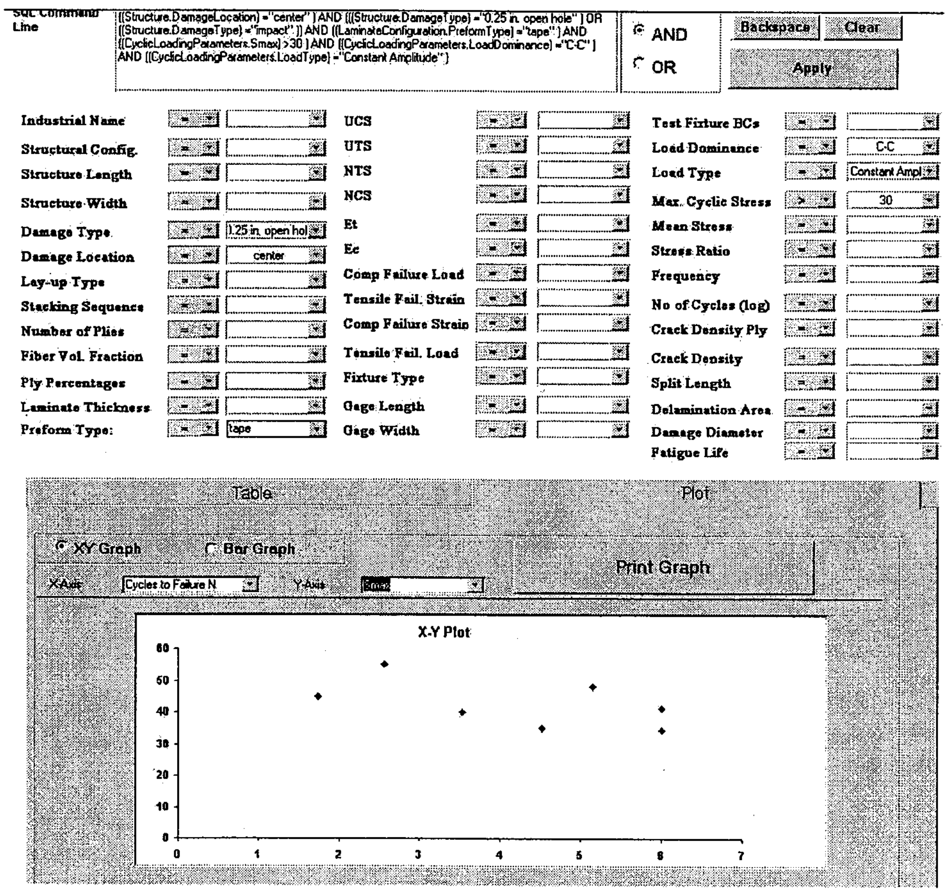
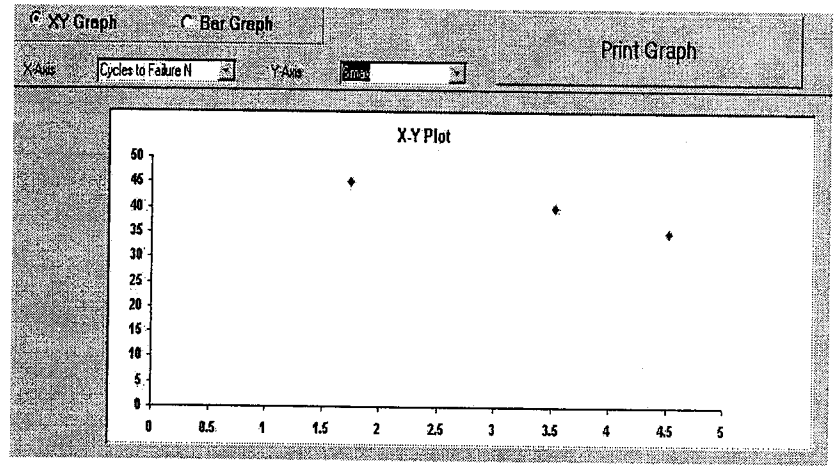


FIGURE 34. S-N PLOT FOR OPEN HOLE AND IMPACTED COMPOSITE SPECIMENS

(a)



(b)

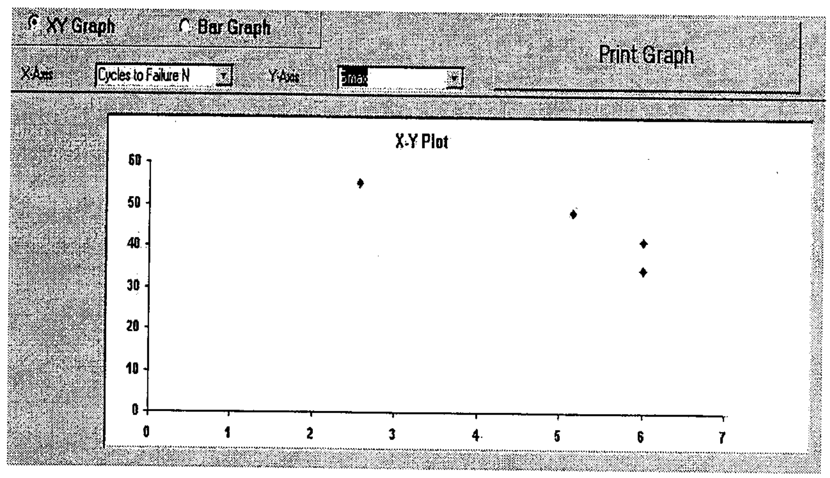


FIGURE 35. S-N CURVES FOR (a) OPEN HOLE AND (b) IMPACTED COMPOSITE COUPONS UNDER CONSTANT AMPLITUDE C-C LOADING

When the two S-N curves are compared, it is evident that the open-hole S-N curve is below the impact S-N curve for the same material system under C-C constant amplitude loading. Thus an open hole is more detrimental than an impact damage in this case. This is contrary to the general findings reported in the composites literature as described in section 3.1. If the impact energy information is retrieved from the system, it can be seen that the impact energy is only 1.55 ft-lb. In full-scale structures, damage caused by impact energies of up to 100 ft-lb is considered as barely visible. Hence, the impact energy level is rather low for this set of data, making the open hole more detrimental.

<u>6.2.5 Similarity Between the Requirements of an Experimental Study and Existing Data in *Durability*.</u>

In this example, the requirements for a composite structure are compared to the existing data in the system. This set of requirements was chosen for a particular structural configuration and fatigue loading parameters which are specific to an experimental study. Some of the required values were not available in the pull-down menus. In such cases, the closest available values were assigned to the parameters and their user confidence values were adjusted accordingly. For numeric inputs, bound values were assigned to track results in a range of values rather than for specific target values.

For the input, a coupon size stitched graphite/epoxy laminate was specified. Damage type was impact and fatigue load type was Modified TWIST Spectrum Loading. In the pull-down menu for preform type, the stitched option was not available, so the tape option was selected and a very low confidence level was assigned (table 24). A similar method was followed for the width of the structure where the available options were far from the specified value.

TABLE 24. ENTRY VALUES FOR CASE 6.2.5

Field	Required Value	Selected Value	Bounds	User Confidence	Parameter Weight
Structural Configuration	Coupon	Coupon		10	7
Structure Length	9	10.51	2	8	5
Structure Width	6	1.503	4.5	2	5
Damage Type	Impact	Impact		10	10
Damage Location	Center	Center		10	5
Preform Type	Stitched	Tape		1	5
Number of plies	26	32	4	9	5
Fatigue Load Type	Modified TWIST	Modified TWIST		10	6
Fatigue Load Dominance	Compression	Compression		10	10
Max Cyclic Stress	40	40	5	6	7
Mean Stress	-15	-15	5	8	5
Number of Cycles	4	4	0.4	8	5
Material Class	Graphite/Epoxy	Graphite/Epoxy		10	7

Figure 36 shows the overall confidence ranking of the output. It should be noted that an overall confidence threshold of 60% was specified and all 15 results are above this threshold value. The top two selections with highest overall confidence of 66.7% fall in the bounds specified for the number of cycles. The following selections satisfy the same amount of requirements except for number of cycles. Number of cycles can be checked by clicking on the selection (the details cascaded folder will appear) and going to the cyclic loading parameters folder. The relatively low rate of confidence is due to the fact that two of the input requirements are not satisfied and very low confidence levels were assigned for these entries.

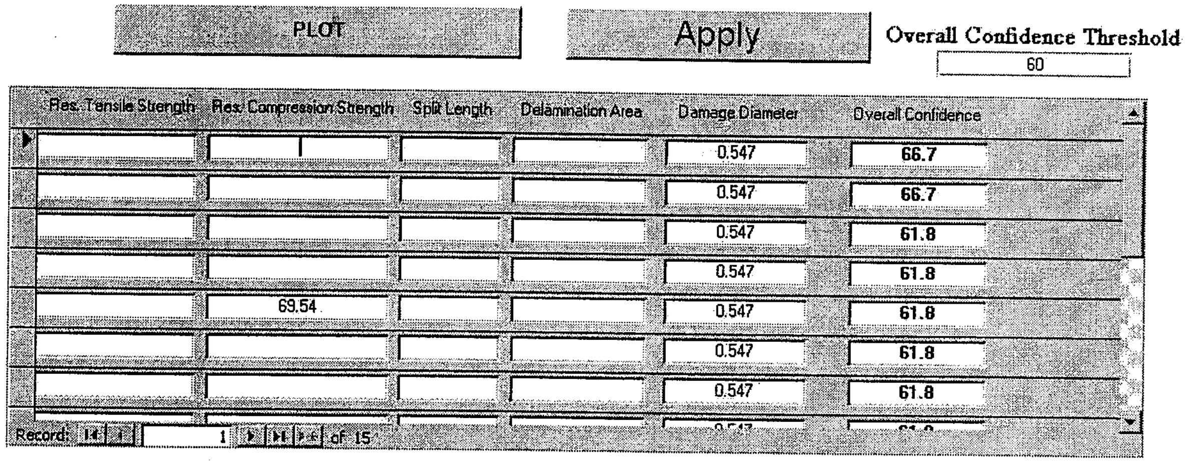


FIGURE 36. OUTPUT FROM EXPERT SOLUTION INTERFACE FOR EXAMPLE 6.2.5

7. RESULTS AND DISCUSSION.

An important advantage of using a structured database for nonstandardized data is that any new piece of data can be used as soon as it becomes available without having to wait for standardization. Information systems offer a solution by providing a user with multiple results and the freedom to make choices. Also, since data is entered in a preformatted manner, comparisons of various data sets are possible.

During fatigue design literature study and data extraction, it was observed that standardization in reporting experimental results of fatigue is even less than it is for impact damage in composites. This fact is a major problem in understanding and predicting fatigue performance of different composite materials and makes it very laborious for the researcher to conduct comparative studies. *Durability* offers partial solution to such difficulty by providing the researcher with all types of results. However, the user still needs to select the parameters that will be used in the analysis. The system can also be used to search for standardization trends in conducting fatigue tests. Standardization is also a benefit for the regulatory agency as data from standardized tests are easier to prove veracious. As more standards emerge, the system can be modified for data entry in terms of these standards.

8. SUMMARY.

Impact damage behavior data of composites has been collected and stored in the developed system. A variety of experimental results were entered in order to make *DamTol* effective over a large selection of parameters and with a spectrum of values for each parameter. The software allows instant comparison of many parameters and their effects on impact damage behavior of composites. It also allows researchers to compare impact damage behavior data from different stages of the building block approach in certification. *DamTol* readily contains data for coupon level, panel level, and element level structures.

Durability can be used for developing and testing fatigue models for specific and general material and loading cases. Data generated from prediction models can be entered into the system and compared against experimental fatigue data using the plotting capabilities of the system. Furthermore, existing experimental data can be queried with broader constraints to capture relationships between different parameters and this information can be used in developing general empirical models. These systems can also be used in research for identifying areas that require experimental studies as well as in investigating the effects of various parameters on the damage behavior.

The systems in their present form can be used for model development. Since they contain experimental data, empirical relationships between parameters can be tracked under input requirements. For example, by using *Durability*, damage growth curves or S-N type curves can easily be obtained under any input conditions. The systems can also be used to compare a prediction model to experimental results by entering data obtained from the prediction model. Also, Expert Solution interfaces can be used to see the similarity between prediction and experiment.

As information systems tools find increasing areas of applicability, composites research should be able to benefit from these tools in problem solving and decision making. Utilization of the ample amounts of data collected through years of experimental efforts will result in better understanding of composites behavior paving the way to a more comprehensive knowledge base of these materials. Information systems storing these data will help current engineers by presenting experiences of the past. Such tools may also aid in the enhancement of existing models by bridging different aspects of composites design and manufacturing.

9. FUTURE WORK.

The methodology used for developing data structures of *Durability* and *DamTol* can be used in other fields of composite. Even though some fields may be common, many of them would need to be deleted and replaced by the pertinent parameters of the subject of interest. The user interfaces can also be used in these new systems by again making the required changes in order to accommodate new parameters. System development attempts were proceeding in composites repair, textile composites, and sandwich composite panel design. Since a certain level of experience has been reached with establishing conceptual data models and turning them into information systems, results of these attempts will be gained in relatively shorter terms compared to the initial study presented in this dissertation.

The research work conducted for this part of the project can be complemented and improved in many aspects. From a software development perspective, the systems can be made web-applicable, they can be incorporated with subroutines that produce prediction model data and they can be filled with more data that may require new data fields. On the other hand, the information systems can be used for knowledge acquisition in order to create a knowledge base on the damage and durability behavior of composites. This type of a knowledge base would be instrumental in the design, analysis, and certification of composite structures. Application of the developed database structuring and user interfaces to other subjects of composites science can be achieved with less effort.

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