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USE OF AN ENGINEERING DATA MANAGEMENT SYSTEM  
IN THE ANALYSIS OF SPACE SHUTTLE ORBITER TILES

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USE OF AN ENGINEERING DATA MANAGEMENT SYSTEM IN THE ANALYSIS OF  
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Abstract

This paper demonstrates the use of an engineering data management system to facilitate the extensive stress analyses of the Space Shuttle Orbiter thermal protection system. Descriptions are given of the approach and methods used (1) to gather, organize, and store the data, (2) to query data interactively, (3) to generate graphic displays of the data, and (4) to access, transform, and prepare the data for input to a stress analysis program. The relational information management system was found to be well suited to the tile analysis problem because information related to many separate tiles could be accessed individually from a data base having a natural organization from an engineering viewpoint. The flexible user features of the system facilitated changes in data content and organization which occurred during the development and refinement of the tile analysis procedure. Additionally, the query language supported retrieval of data to satisfy a variety of user-specified conditions.

Introduction

The metal primary structure on the external surface of the Space Shuttle Orbiter is protected from the thermal environment by an array of over 30,000 RSI (reusable surface insulation) tiles as discussed in reference 1. Assessment of the integrity of this thermal protection system requires that a stress analysis be performed on each tile. A stress analysis program, reference 2, was developed for this purpose. The analysis accounts for the nonlinear material properties of the strain isolator pads used to attach the tiles to the metal surface of the Orbiter. This analysis requires geometry definition, aerodynamic and vibroacoustic loads, Orbiter surface deflections, and materials data for each tile. This data existed in many forms in various engineering reports. The gathering and preparation of input data for the analysis of a single tile was a time-consuming process (required approximately 1 man-day per tile) when done by hand. Therefore, there was a need for the capability for automatic storage and retrieval of data needed for analysis so that large numbers of tiles could be analyzed in a timely manner.

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The purpose of the present paper is to describe the approach used to incorporate an advanced engineering data management system in the analysis process for Space Shuttle Orbiter tiles. The approach utilizes the Relational Information Management (RIM) system, reference 3, which was developed as part of the NASA-sponsored IPAD project, reference 4. The interactive query language of the RIM system is used to make selected on-line retrievals of any stored data. A FORTRAN interface, which is a set of user callable RIM subroutines, is used extensively by other computer programs needed for communication of data between the nonlinear analysis program and RIM.

The contents of this paper include a brief discussion of the nonlinear tile analysis procedure. Next, the organization of the data base of engineering data needed for tile analysis is described. Methods of retrieving data from the data base are discussed and graphical displays of the tile data are illustrated. The functions of the computer programs and data files making up the automated data management/analysis system are explained. This system automates the entire process beginning with access of tile data from RIM through execution of the nonlinear stress analysis program and display of results. Application of this automated system to critical analysis studies of over 3,000 tiles is described. This significant analysis effort was performed in a timely manner (less than a day) and is typical of the studies performed to aid in flight-readiness certification of the tiles for the first Orbiter flight. The discussion concludes with general observations and assessments regarding the large-scale engineering application of relational information management procedures based on experience from development and use of the tile analysis system.

Definitions

The following terms are defined in the context that they are used in this paper:

Attribute	An alpha-numeric name used to identify a column of data items in a relation.
Data Base	An organized collection of interrelated data which is stored in accessible form including the actual data items and all their associated directory information.
Data Item	The smallest unit of named data; herein refers to a single value of engineering data.

DDL	Data Definition Language, used to establish a data base schema.
DML	Data Manipulation Language, used to change the contents or organization of a data base.
FORTRAN Interface	A library of FORTRAN-callable subroutines which are used to move a tuple from the data base to an array in a user program or vice versa.
Query Language	A user language containing Boolean conditional clauses for selecting desired data.
Relation	A two-dimensional table of data items organized in rows (tuples) and columns (attributes) and referred to by an alphanumeric name.
Schema	An overall organizational chart used to describe a data base. It gives the names of the attributes and defines the relations between them, i.e., a framework into which values of the data items are fitted.
Tuple	A row of data items in a relation.

#### Tile Modeling and Analysis Procedure

Approximately 8,000 tiles in a large region of the lower surface of the Orbiter wing and fuselage are considered in this study. This region is shown in figure 1 inside the outlined area of the lower surface planform which is divided into tile zones W-3, W-4, MF-5, and MF-6. The geometric planform shapes of each tile in this region are shown in the computer-generated plot for the right-hand side of the Orbiter. Assessment of the structural integrity of these tiles using a stress analysis procedure requires the generation of an analytical model for each tile which represents the tile physical description, material properties, and applied loads. This section contains characteristics of a typical tile analytical model and the corresponding stress analysis procedure.

#### Tile Physical Description and Modeling

The components in a typical tile installation are shown in figure 2(a). The tiles are attached to the Orbiter metal surface or substrate by an intermediate strain isolator pad (SIP) as shown in figure 2(b). This pad prevents motion of the Shuttle structure produced by thermal or aerodynamic loading from cracking the brittle tile material. This SIP material has nonlinear stress-displacement properties as indicated in reference 5. These nonlinear properties, illustrated in figure 2(c), are obtained from material tests and are represented in the analysis procedure as tables of stress-displacement points. A filler bar is used as a thermal barrier around the perimeter of the SIP to

prevent direct heat radiation or convection to the skin between tiles. This filler bar is not attached to the tile and is represented by a material curve which allows no tensile stress as shown in figure 2(c). To provide capability to analyze all tile configurations, the SIP's are defined with an arbitrary boundary made up of linear segments including cutouts for instrumentation or other penetrations. The analysis process requires integration of stresses over the SIP. For this purpose, the SIP and/or filler bar surfaces are divided into triangular regions each containing a mesh of subtriangles as shown in figure 2(d). The integrated stress is the sum of contributions of assumed linear stress distributions over each subtriangle. The mesh refinement can be varied to give any desired solution accuracy.

#### Tile Loads

Stresses in the strain isolator pad are caused by pressures acting on the tile which result from the aerodynamic environment, inertia forces from vibratory motion of the tile, and deflections of the substrate to which the SIP is attached. The various tile loading sources which are considered are shown in figure 3. The parameters needed to define the steady aerodynamic loads include the pressure change across a shock for both separated and unseparated flow, aerodynamic pressure gradients in the streamwise and transverse directions, and a reference pressure which is related to the ambient pressure. Aerobuffet loading is given as forces and moments measured from wind-tunnel tests. The load on the tile caused by a lag in venting the interior tile pressure during Orbiter ascent is taken to be a constant value for all tiles. The skin friction on the external surface is a function of the distance of the tile from the leading edge of the Orbiter planform, a quantity that is calculated and stored for each tile. The substrate deformation for vibroacoustic loading has a specified amplitude and wavelength corresponding to the structural panel width. The static substrate deflection is deformation of the skin between stiffeners on the panel caused by buckling or pressure differentials across the skin. In the analysis procedure, the deflections of the substrate are positioned relative to the tile to give maximum stress. The maximum positive amplitude of the long wavelength is positioned at the center of the tile and the maximum negative amplitude of the short wavelength is positioned under the front corner of the tile. These substrate deflection positions were guided by results presented in reference 6.

The data needed to describe this load environment are defined in relation to aerodynamic and structural panels defined on the surface of the Orbiter. The aerodynamic load parameters are taken to be constant within each of the aerodynamic panels shown in figure 4. The boundaries of the wing panels are located at constant fraction of semispan locations and constant percent chord locations, the usual nondimensional coordinates used by aerodynamicists. Only two aerodynamic panels, corresponding to the MF-5 and MF-6 tile regions, are used for the fuselage.

The vibratory inertia loading on the tiles and corresponding substrate deflection, collectively referred to as vibroacoustic loads, and the static substrate deflection are defined in relation to the structural panels shown in figure 5. The boundaries of the wing structural panels are along ribs and spars and along frames and stringers on the fuselage. The vibroacoustic tile loading is a function of distance from the panel boundary.

#### Tile Analysis Procedure

In the baseline or original TPS configuration, the tiles had uniform properties through the thickness (undensified tiles). During early testing of the undensified TPS tiles under externally applied loads, failure was found to occur in the tiles adjacent to the plane where they were bonded to the SIP. Based on this observation, it is assumed that the failure stress is excessive through the thickness or normal stress in the SIP. If this calculated normal stress exceeded a specified allowable stress, the tile was removed and densified (strengthened by a thin layer of impregnated material at the tile's inner surface).

A tile analysis program based on the above considerations was developed to calculate these normal stresses in the SIP, reference 2. The analysis procedure is a generalization and extension of the basic method described in reference 7. The tile can be assumed to be a rigid body, as shown in reference 8, with six degrees of freedom (three translations and three rotations) at its center of gravity. External loads are applied to the tile as concentrated forces, pressures, and/or inertially equivalent accelerations (g-load). The substrate under the SIP can be given a prescribed shape to represent mismatch from the manufacturing process, warpage of the tile, and/or deformations of the external surface of the structure such as those caused by buckling.

A Newton iteration procedure is used to calculate the displacements and rotations of the rigid tile for which the reaction forces from stresses in the SIP and filler bar material are in static equilibrium with the applied loads. Once equilibrium is established, the maximum stress and its location in each SIP is calculated.

#### Organization of Engineering Data

Tile geometry, material properties, and applied loads are required as input to the stress analysis program. To provide timely results for a large number of tiles, it was essential to automate the data management and analysis process. The first task in developing such a capability was to gather, organize, and store the required data in a computerized form which could be accessed from a single source. This data organization task was completed in approximately 6 man-months. This effort required the development of numerous data preparation programs to convert the engineering data

from its original form to the desired form for computer storage. A technical description of the resulting data items and the methodology used to organize all tile analysis data is given in this section.

#### Use of Relational Model

All engineering data required to perform a nonlinear stress analysis of the tiles was stored using the Relational Information Management (RIM) system. RIM, which is based on the relational model, reference 9, was chosen because it is well suited to the tile analysis problem since information related to many separate tiles needs to be accessed individually. Specifically, each tile is related to geometrical, physical, and material properties and to a variety of load sources. The data are organized in the form of tables referred to as relations. Every relation has a unique user-assigned name. Typical example relations, NEWAPANL, STS1TRAJ, and NEWLOADS are illustrated in figure 6. Each column in a relation is referred to by a name or attribute and each row is called a tuple. A data definition language (DDL) is available in RIM for creating a relation by specifying the names of its attributes, defining the data type for each attribute to be either integer, real, or text, and specifying the dimension of each attribute. These definitions of attributes and relations (collectively referred to as a schema) are stored in the data base. Subsequently, other RIM utilities are used to load tuples of data items into the relations. Data are selected for retrieval in the form of a tuple, or multiple tuples. Generally, data are retrieved by specifying the relation name which contains the data and a Boolean expression to be satisfied by the values of the attributes.

A well-planned schema is important to allow straightforward, efficient storage and retrieval of the data. A variety of schema definitions is possible for a given application. For example, a very simple schema for the tile analysis problem is a large, single relation with each tuple containing all the data required for analysis of a particular tile. Such a schema would be cumbersome to form and/or change.

Herein the data are organized in several relations each containing a table of data in the logical form that would normally be used to solve the engineering problem. This type organization is illustrated by the relations shown in figure 6 which are used in the definition of aerodynamic loads. For clarity, the first attributes in each relation are the independent variables followed by attributes for the dependent variables. This convention is illustrated by relation NEWLOADS at the bottom of figure 6 where the dependent variables SHOCKJUMP and ABSHKCPRMS which are parameters defining aerodynamic shock and aerobuffet loads are a function of the independent variables AEROPANL, MACHNO, and ALPHA which define a particular aerodynamic panel, the Mach number, and angle of attack, respectively.

Many of the relations contain attributes which are set up to refer or point to corresponding attributes in another relation, allowing the data to be related in a hierarchical or network manner. If, as an example, a tile part number (PARTNO) is specified, the aerodynamic panel containing the tile is specified by the identifier AEROPANL in relation NEWAPANL. A point in the flight trajectory is specified by selecting a Mach number MACHNO, in relation STS1TRAJ. The corresponding angle of attack, ALPHA, dynamic pressure, QPSF, and ambient atmospheric pressure, PINF, are then retrieved. Then the aerodynamic panel, Mach number, and angle of attack are used in relation NEWLOADS to determine the pressure differential across a shock, SHOCKJUMP, and an aerobuffer load parameter, ABSHKCPRMS. The data values for MACHNO and ALPHA in relation STS1TRAJ do not have corresponding numerical values in relation NEWLOADS so interpolation is required.

#### Schema for Tile Data

All relations and attributes used in the analysis of Orbiter tiles are shown in figure 7. Each relation name is underlined and followed by a list of all attributes in the relation. These attributes are shown in transposed form as a column for graphical purposes instead of as a row corresponding to tuples as shown in the standard form of figure 6. Some of the attributes appear in more than one relation in figure 7 indicating a correspondence or linking of attributes between relations. Descriptions of the engineering data contained in the relations of figure 7 are given in the remainder of this section.

Geometry and Material Properties Data. Each tile on the Orbiter is identified by attribute PARTNO, a unique nine digit part number. Tile geometry is described by the coordinates of points at the tile corners. This corner point definition of geometry restricts the tiles which can be considered to those whose inner and outer surfaces have relatively small curvature. The corner points were originally defined in various local coordinate systems but were transformed to a single coordinate system specifying their location on the Orbiter before storing. This geometry data was stored in relation XYZO as shown at the lower left of figure 7. Each tuple in this relation defines a single tile corner point with attributes giving the part number, drawing number, inner or outer surface (mold line) indicator, the local coordinates, number of the transformation equation, and the resulting Orbiter coordinates. Each tile requires as many tuples as it has corner points.

To minimize data storage requirements, the tile geometry is stored for only the right-hand side of the Orbiter, by taking advantage of the symmetric tile pattern in the zones considered. While tile geometry is symmetric, the material properties associated with the tiles are not necessarily the same on corresponding tiles. During the tile flight certification process,

each tile was loaded to a specified tensile proof stress using a vacuum chuck and a proof test fixture. Tiles on opposite sides of the Orbiter were not necessarily proof loaded to the same value causing SIP properties, which are dependent on proof load history, to be different. Further, tiles which failed the proof test were removed and densified. The relation TIPSDATA (upper right of figure 7) contains tuples of information for all tiles with an indicator denoting the right- or left-hand side of the Orbiter, the part number of the opposite or symmetric tile, whether or not the tile has been strengthened by densification, and the stress level to which the tile was proof loaded.

The loading history, hence the tile proof level, affects the material properties of the strain isolator pad used to attach the tile to the Orbiter. Two relations, MATINDEX and MATCURVE, are used to store those material properties. The first relation, MATINDEX, contains the following attributes that are parameters needed to define a particular material curve: the pad type, either filler bar or SIP; the pad thickness; the proof test stress; and a corresponding material number. The points on the stress-displacement curves are stored in relation MATCURVE for each material number.

Load and Stress Data. The aerodynamic load parameters are taken to be constant within each of the aerodynamic panels shown in figure 4. The aerodynamic panel corresponding to each tile is given in relation NEWAPANL as shown in figure 7. The set of aerodynamic parameters that give greatest tile loads within each panel were reduced from wind-tunnel tests for a range of Mach numbers and angles of attack and stored in relation NEWLOADS. All aerodynamic parameters that were used are shown in figure 7 while only SHOCKJUMP and ABSHKCPRMS are shown in figure 6 for illustrative purposes. The aerodynamic load parameters are nondimensionalized with respect to dynamic pressure for use with various flight trajectories. The trajectory data for the first Orbiter flight is given in relation STS1TRAJ.

Data preparation programs were used to determine the aerodynamic and structural panel numbers for each tile and calculate the distance of the tile from the edge of its structural panel. The corners of the structural panels shown in figure 5 are defined in relation SUBPANL and the corresponding data values for the vibroacoustic loads and substrate deflections are contained in relations VIBAC and SUBDEFL as shown in figure 7.

The stresses which were calculated during this study are stored in relations similar to STRS4-24-1 as shown in figure 7. The "4-24-1" refers to the date that these stresses were calculated. The actual tile proof stress, ACTPROOF, is divided by the maximum calculated stress, STRESSMX, to give the stress ratio, SRATIO. The values of the stress ratios were examined to determine the relative safety margins for the tiles.

Miscellaneous Data. Miscellaneous tile data are contained in relation DIRECT including the substrate panel identifier for each tile, SUBSPANL, and the distance of the tile from the panel edge, CGTORIB. The tile location with respect to the Orbiter planform is given by the tile center of gravity, CGXI and CGYI, and the distance from the planform leading edge, CGTOLE, which is used in calculating the skin friction force. Physical properties of tile thickness, SIP thickness, and tile density are referred to by the attributes TILETHCK, SIPTHCK, and TILEDENS, respectively.

#### Data Retrieval and Display

The use of the RIM system for managing the Orbiter tile data was greatly facilitated by its efficient, flexible, easy-to-use capabilities for data retrieval. The capabilities provided ready access to the tile engineering data for display in a user selected form. The methods used to retrieve, manipulate, and display the tile data are discussed in this section.

#### Query Language

A relational query language, which contains Boolean conditional clauses for selecting desired data, is available in RIM. This language has the flexibility to support retrieval of data to satisfy a variety of conditions many of which were not anticipated during the organization of the tile data base. The syntax of the query language statements makes them self-explanatory. In general, the statements specify an operation to be performed, specify the relation containing the data, and define conditions to be satisfied by data values in selected attributes of the relation.

Examples of typical queries used in the tile analysis application are given in Table 1. Query (a) was used to generate the listing of tuples from relation NEWLOADS shown in figure 6. The SELECT operation requests printing of data values in attributes AEROPANL, MACHNO, ALPHA, SHOCKJUMP, and ABSHKCPMS from tuples in relation NEWLOADS which satisfy the conditions given in the "WHERE" clause. The underlined words in the example queries define the function of the query with the other words referring to any relation names, attribute names, and data values in the data base that can be used logically in a statement. For the number of relations and attributes used in the tile data schema of figure 7, the interest of a particular user determines what queries might be made and the examples in Table 1 are only an illustrative sample. Queries similar to (b) are used to assess the calculated stress data. In the example shown, the tuples are printed in ascending order of the value of SRATIO which is the tile proof stress divided by the calculated stress. The TALLY operation in query (c) causes a table to be printed which contains each of the different values of proof stresses that were used and a tally of the number of tiles corresponding to each proof stress. The minimum tile thickness is returned by query (d). Query (e) is used to

determine the number or count of undensified tiles on the left-hand side of the Orbiter.

A query can be used to retrieve information from a single relation. For unanticipated queries, a single relation having all the attributes to satisfy a desired condition may not exist. In this case, a new relation which contains the proper attributes may be formed using the data manipulation language (DML) which is described next.

#### Data Manipulation Language

Data manipulation commands are available in RIM to change the contents and organization of the data base. Selected data manipulation commands are illustrated by the examples in Table 2. The CHANGE command shown in example (a) changes the value of the dynamic pressure QPSF from 622.0 to 612.0 in the first tuple of relation STSITRAJ shown in figure 2 where the Mach number MACHNO equals 0.93. Other commands, which are not illustrated, are available to change the contents of a relation by adding or deleting tuples of information.

The organization of the data base schema can be changed by extracting or combining attributes of existing relations to form new relations. Relational algebra commands with set theoretic operations are used for this purpose. These commands are illustrated in examples (b)-(f) to create a new relation PLOTDATA which can be used for plotting the values of tile thickness for the tiles in aerodynamic panel number 3. The INTERSECT operation in example (b) forms a new relation TEMP based upon tile part number, PARTNO, which contains attributes CGTOLE and TILETHCK from relation DIRECT and AEROPANL from relation NEWPANL that have the same tile part number PARTNO. In example (c), the relation PLOTDATA having attributes PARTNO and TILETHCK for tiles in aerodynamic panel 3 is created using the PROJECT operation. In example (d), the attribute name TILETHCK is changed to VALUE.

In example (e), an inverted file is formed with tile part number PARTNO in relation PLOTDATA specified as the key attribute. This inverted file contains a set of pointers leading to the storage location of the tuple corresponding to a specified tile part number. Use of inverted files provides much faster response to queries involving the key attribute than performing sequential searches through data items of the specified attribute. Inverted files can be created and deleted as needed using the BUILD KEY and DELETE KEY operations. Inverted files are often needed to provide an acceptable response time for data access from relations containing a large number of tuples, but they require additional auxiliary storage space for the pointer information. In example (f), the temporary relation TEMP is removed since it is no longer needed.

#### FORTRAN Interface

The FORTRAN interface permits access to the data base from separate programs. This interface is a library of FORTRAN-callable

subroutines which are used to move a tuple from the data base to an array in the user program or vice versa. An example listing which illustrates the use of the FORTRAN interface is shown in Table 3. The statements in this listing perform the same function as query (b) shown in Table 1, to print calculated stress information.

Initially, arrays are established to accommodate a conditional (WHERE) clause and a tuple of data each of which can contain a mixture of real or integer values. The seven words in the conditional clause are stored in successive locations of the KLAUS1 array. The interface subroutine RIMHUNT is called to locate all tuples which satisfy the specified conditional clause. These tuples are then sorted by ascending order of the values in the attribute SRATIO using the RIMSORT interface subroutine. Then subroutine RIMGET is used to move the tuples into the program array A1 one at a time for printing until a nonzero value of RIMSTAT is returned indicating that all qualifying tuples have been accessed.

To support navigation through relations in a hierarchical or network structure, RIM allows multiple RIMHUNT condition sets to be in effect at the same time. For example, the functions performed in examples (b) and (c) of Table 2 could be handled with the FORTRAN interface by first using a RIMHUNT to locate all tuples in relation NEWAPANL which have AEROPANL equal to 3. A second, subordinate RIMHUNT could then be used to locate all tuples in relation DIRECT which have the same part number as those tuples returned by the first RIMHUNT by using the value of PARTNO in the second conditional clause. This nesting of RIMHUNT conditions is used extensively in the data access program of the automated stress analysis system.

#### Graphical Display of Data

Graphical displays of the tile data were important for validating or correcting the data after it was loaded into the data base. A separate plotting program was developed for this purpose using the FORTRAN interface to retrieve the stored data. This program generates a planform view of tile geometry with each tile annotated with any related data which can be displayed on an interactive terminal and/or off-line plotter. Such a display is illustrated by the planform view of tiles in the plot in figure 1.

The tile geometry is provided by the corner point coordinates in relation XYZO. The plotting program is greatly simplified by using the relational algebra capabilities of the data management system to select which tiles and which related data values should be used for a given plot. This selection is achieved by forming a relation called PLOTDATA containing tuples with a tile part number and a corresponding attribute to be plotted. Such a relation can be formed using DML statements as illustrated in the previous subsection by commands (b)-(f) of Table 2. The resulting plot of tile

thicknesses for all tiles in aerodynamic panel 3 is shown in figure 8.

During the tile study, graphic displays were used to assess the calculated stress data. Although data for each tile zone were stored in a separate data base, it was sometimes desirable to have composite pictures of the calculated results. For this purpose, the data in all pertinent relations were combined in a common data base. Such a common data base was used to create the display of 1,000 undensified tiles on the lower surface of the Orbiter in figure 9. These tiles are annotated with an integer 1-10. Each integer indicates a group of 100 tiles from a table sorted in order of decreasing criticality of their calculated stresses (i.e., ascending values of SRATIO).

#### Automated Data Management/Analysis System

The data management system RIM together with the analysis programs were combined into a system which was used to calculate, display, and interpret tile analysis results. The resulting automated data management/analysis system is a collection of computer programs and data files needed for data communication between the non-linear stress analysis program (ref. 2) and RIM (ref. 3). This system can be used in three different modes as indicated in figure 10. The first mode is to use the RIM Interactive Executive as a stand-alone system and access any of the desired engineering data using the DDL, DML, and query languages of RIM. This capability is usually accessed from an interactive terminal with keyboard input and printed output. In the second mode, graphical displays of selected data are generated on an on-line terminal and/or off-line plotter using the separate program developed for this purpose. The third user mode is to perform automated stress analysis. This mode requires use of pre- and postprocessors containing several computer programs and data files to connect the stress analysis program with the RIM data files. The development of the pre- and post-processors was a significant task requiring the same level of effort as the creation of the tile data base itself. Neither the stress analysis program nor RIM were modified during development of the automated system.

User-prepared input data are required to select the tiles and to specify load conditions to be used in a particular analysis. This information is used by the preprocessor to extract all data from the RIM data files which are required for a stress analysis and to generate an analytical model of the tile and its applied loads.

The preprocessor makes extensive use of the RIM FORTRAN interface subroutines. These subroutines are used to support repetitive queries that are tailored to extract all data necessary to analyze the selected tile part numbers at the specified Mach number selected from a prescribed Shuttle Orbiter flight trajectory. The resulting

analytical model is in the form of a card image input file which is used by the nonlinear stress analysis program. The maximum stress on each SIP is computed for each load case that is specified, thus completing the automated stress analysis process. This calculated stress information is usually subsequently processed to determine the load case which produces the largest stress for each tile. These stress values are compared with the allowable stresses and then all pertinent stress data are stored in the RIM data files using a postprocessor. Various user initiated queries are then made to assess the calculated stress data.

The analysis system is operational on the CDC NOS 1.3 operating system. NOS control statements are used to invoke programs and data files as needed in the stress analysis process. Because of computing time requirements for the nonlinear stress analysis procedure, interactive use of the system is effective when only a few cases are to be analyzed. For the analysis of a large number of tiles and/or load cases, operation of the system in a batch mode is desirable.

#### Use of Automated Analysis System

The automated data management/analysis system required a 10 man-month effort for development. Approximately 60 percent of the effort was required to gather, organize, and store the data into RIM and the other 40 percent involved the development of computer programs to serve as an interface between the stress analysis program and the RIM data base. The data base contains approximately 600,000 words of engineering data necessary to analyze the 8,000 tiles on the lower surface of the wing and fuselage (figure 1). An additional 250,000 words of data is used for schema descriptions and inverted files that are retained so that 850,000 words of disk storage are required.

The largest application of this system was the analysis of all 3,137 undensified tiles on the lower surface of the Orbiter. A nonlinear stress analysis performed for each of these tiles required approximately 9.5 hours of central processing time on CDC CYBER 175 computers. This analysis was divided into several individual runs, each involving approximately 100 tiles. This division into smaller runs was a precautionary measure to minimize the effect of a software or hardware malfunction. It also allowed an opportunity for incremental review of results while taking advantage of the multiprogramming capabilities of the CYBER computer. Over 3,000 tiles were analyzed in one day in contrast to the previous manual analysis which required 1 man-day per tile. A typical analysis of 100 tiles required 0.8 minutes for execution of the data access and analytical model generation programs and 20.0 minutes for the nonlinear stress analysis program. Thus, the data access and model generation time is minor compared to the time required for stress analysis. Accordingly, it is cost-effective to

regenerate the analytical models of the tiles for input into the stress analysis program each time an analysis is made rather than save the models on auxiliary storage.

The tile schema shown in figure 7 is the one used at the conclusion of the study. During the development of an automated analysis system to access this data, many changes in data organization and data content were made. These changes reflected the evolutionary nature of an engineering analysis process. For example, during development of the system, there was a continuing modification of the loads data as various wind-tunnel tests were completed accompanied by changes in criteria used to apply these loads to the tiles in combinations to give realistic design conditions. Hence, an important feature of an engineering data management system is the flexibility for changing the contents, not only addition or deletion of data items but also reorganization or restructuring of the data base schema.

The integrity of the software system and security of the data are manifested by the fact that no data were inadvertently destroyed or lost because of system malfunction during development and use of the tile analysis system. The use of the automated system proved to be successful in producing analysis results for large numbers of tiles in a timely manner. These results aided in the flight-readiness certification of the tiles for the first Orbiter flight and aided in determining which tiles should be removed and densified between the first and second Orbiter flights.

#### Observations and Assessments

The application of an engineering data management system was found to be very effective for the analysis of Space Shuttle Orbiter tiles. By use of this system, thousands of tiles can be analyzed in 1 day in contrast to the 1 man-day of effort per tile required when input was prepared manually. The experiences of organizing the tile data base, developing programs to provide communication between the data base and the analysis program, and use of the resulting automated system led to the following general observations and assessments regarding application of engineering data management systems:

1. The selection of a data management system is highly dependent on the application. In the present application, each tile is related to geometrical, physical, and material properties and to a variety of load sources. A relational system is, therefore, well suited to the tile analysis problem because such information related to many separate tiles needs to be accessed individually.

2. The capability to have attributes in one relation point to attributes in other relations in a hierarchical or network structure is important to allow a natural organization of the tile analysis data from an engineering viewpoint.

3. The same attribute was often used in different relations but the numerical values of the data items did not necessarily correspond because the values came from diverse sources. Hence, in this engineering application the requirement for interpolation for data values between tuples was prevalent.

4. The evolutionary nature of an engineering analysis process makes it important to have a data manipulation language to change the contents of the data base not only by addition or deletion of data items but also by reorganization of the data base schema.

5. The use of a relational query language, including set theoretic operations and Boolean expressions, supports retrieval of data to satisfy a variety of conditions that may not be anticipated in advance.

6. The DDL, DML, and query languages in the RIM Interactive Executive provided efficient, flexible, easy-to-use capabilities for data storage, manipulation, and retrieval. These languages required a minimum "learning curve." Proficient use of RIM was made in less than 1 man-month by the authors of this paper, who had no previous experience with relational data management systems.

7. Interface subroutines are essential to permit the accessing of data from separate analysis programs. Development of programs to communicate between a data base and engineering programs is a significant task and requires the same level of effort as creating the data base.

8. Pre- and postprocessors are used to connect the previously existing nonlinear stress analysis program to the RIM data base. This interface approach allowed stand-alone versions of the analysis program and RIM to be used to perform many special purpose analyses needed to guide development and provide independent accuracy checks of the automated system.

9. Graphical displays are essential for checking and assessing the contents of a large engineering data base.

#### Concluding Remarks

An automated system which combines advanced engineering data management procedures with a nonlinear stress analysis process has been used to analyze large numbers of tiles on the Space Shuttle Orbiter. This development illustrates a large-scale engineering application of relational information management software for relating each tile to its geometrical, physical, and material properties, and to a variety of applied loads. Descriptions are given of the approach and methods used (1) to gather, organize, and store the data, (2) to query data interactively, (3) to generate graphic displays of the data, and (4) to access, transform, and prepare the data for input to a stress analysis program. The relational information management

system was found to be well suited to the tile analysis problem because information related to many separate tiles could be accessed individually from a data base having a natural organization from an engineering viewpoint. The flexible user features of the system facilitated changes in data content and organization which occurred during the development and refinement of the tile analysis procedure. Additionally, the query language supported retrieval of data to satisfy a variety of user-specified conditions.

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Table 1 Example usage of query language

- (a) SELECT AEROPANL MACHNO ALPHA SHOCKJUMP +  
ABSHKCPRMS FROM NEWLOADS WHERE AEROPANL +  
EQ 4 AND MACHNO GE .95 AND MACHNO LE 1.10
- (b) SELECT ALL FROM STRS4-24-1 SORTED BY SRATIO +  
WHERE SRATIO GE .750 AND SRATIO LE .825
- (c) TALLY ACTPROOF FROM TIPSDATA WHERE +  
DENSIFIED EQ N
- (d) COMPUTE MIN TILETHK FROM DIRECT
- (e) COMPUTE COUNT DENSIFIED FROM TIPSDATA +  
WHERE DENSIFIED EQ N AND LEFTORRT EQ L

Table 2 Example usage of data manipulation language

- (a) CHANGE QPSF TO 612.0 IN STS1TRAJ +  
WHERE MACHNO EQ 0.93
- (b) INTERSECT DIRECT WITH NEWAPANL FORMING TEMP +  
USING PARTNO CGTOLE TILETHCK AEROPANL
- (c) PROJECT PLOTDATA FROM TEMP USING +  
PARTNO TILETHCK WHERE AEROPANL EQ 3
- (d) RENAME TILETHCK TO VALUE IN PLOTDATA
- (e) BUILD KEY FOR PARTNO IN PLOTDATA
- (f) REMOVE TEMP

Table 3 Example usage of FORTRAN interface

```

DIMENSION KLAUS1(50),CLAUS1(50),KA1(100),A1(100)
EQUIVALENCE (KLAUS1,CLAUS1),(KA1,A1)
0
0
0
KLAUS1(1) = 10HSRATIO
KLAUS1(2) = 10HGE
CLAUS1(3) = 0.750
KLAUS1(4) = 10HAND
KLAUS1(5) = 10HSRATIO
KLAUS1(6) = 10HLE
CLAUS1(7) = 0.825
CALL RIMHUNT (10HSTRS4-24-1,KLAUS1,7,1)
CALL RIMSORT (10HSRATIO)
9 CONTINUE
CALL RIMGET (10HSTRS4-24-1,A1,1)
IF (RIMSTAT.EQ.0) 1,2
1 WRITE(6,5) KA1(1),KA1(2),A1(3),A1(4),A1(5),A1(6)
5 FORMAT (1X,2I10,4F10.3)
GO TO 9
2 CONTINUE
0
0
0

```

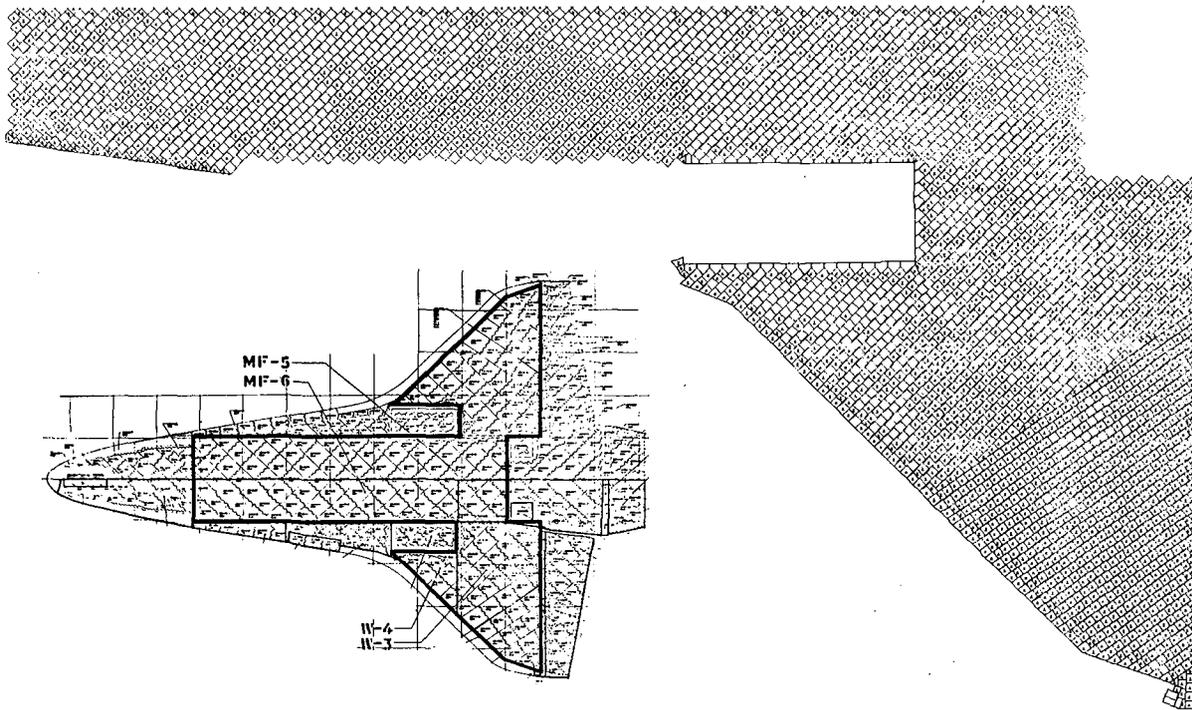
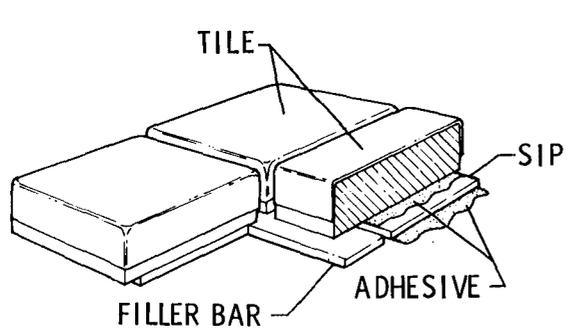
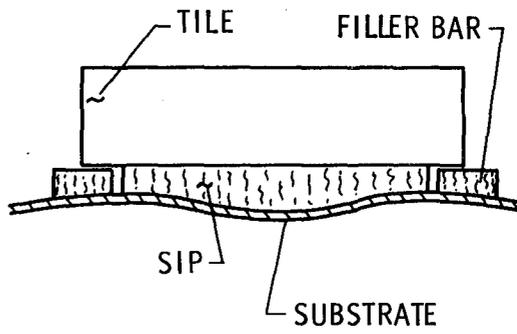


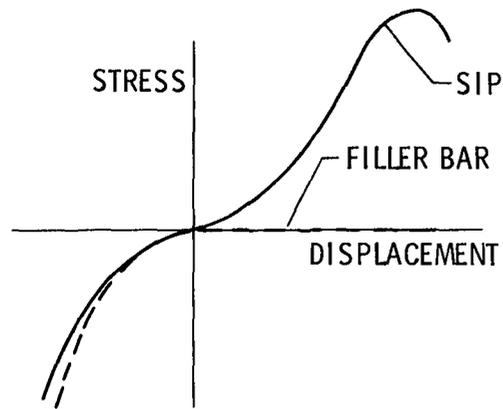
Fig. 1 Regions of Orbiter tiles included in automated data management system.



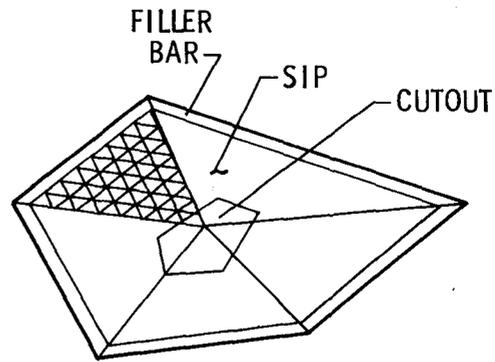
(a) TYPICAL TPS INSTALLATION



(b) TPS ARRANGEMENT



(c) MATERIAL PROPERTIES



(d) NONLINEAR MODELING

Fig. 2 Analytical modeling of thermal protection system.

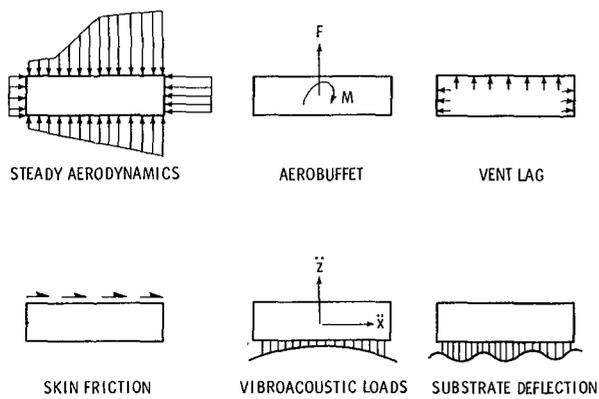


Fig. 3 Applied loads used in tile stress analysis.

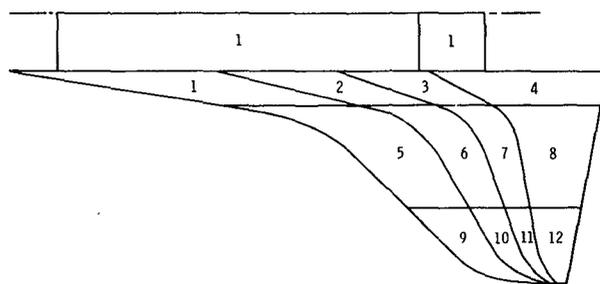


Fig. 4 Aerodynamic panels used in the definition of aerodynamic loading parameters.

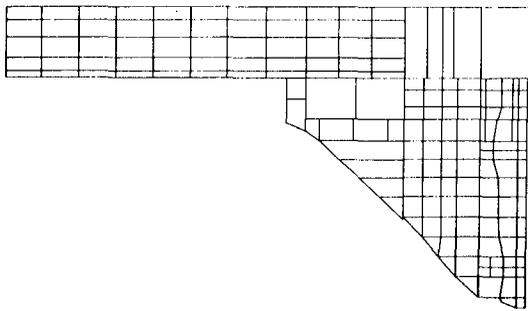


Fig. 5 Structural panels used in the definition of substrate deflections and vibro-acoustic loads.

RELATION NEWAPANL

PARTNO	ETA	XOC	CHORD	AEROPANL
191013071	0.3339951	0.6935504	662.01055	3
190002121	0.2211589	0.7106694	990.32901	4
191013152	0.2933740	0.7709775	780.20517	4
191014066	0.6409095	0.2424357	334.80461	5
191012155	0.4378044	0.4900482	459.88206	6

RELATION STSITRAJ

MACHNO	ALPHA	QPSF	PINF
0.9300000	-3.6300000	622.00000	1019.4700
0.9600000	-3.7000000	627.00000	979.47000
1.0000000	-3.8600000	632.00000	910.97000
1.0400000	-3.8600000	635.00000	844.65000
1.1200000	-3.7100000	636.00000	719.02000

RELATION NEWLOADS

AEROPANL	MACHNO	ALPHA	SHOCKJUMP	ABSHKCPRMS
4	0.9500000	-4.0000000	0.5940000	0.1100000
4	1.0500000	-4.0000000	0.5360000	0.0630000
4	1.1000000	-4.0000000	0.5260000	0.0730000
4	0.9500000	4.0000000	0.5770000	0.1100000
4	1.0500000	4.0000000	0.4250000	0.0630000
4	1.1000000	4.0000000	0.4880000	0.0730000

Fig. 6 Sample relations showing typical data values.

DIRECT	SUBDEFL	STSITRAJ	NEWAPANL	TIPSDATA
PARTNO	SUBSPANL	MACHNO	PARTNO	PARTNO
DRAWNO	LOADNO	ALPHA	ETA	LEFTORRT
DASHNO	FLTCOED	QPSF	XOC	OPPPARTNO
ARRAYNO	DEFLSKIN	PINF	CHORD	DENSIFIED
IMLPTS	DEFLSTRNG		AEROPANL	ACTPROOF
OMLPTS	WAVESKIN	<u>NEWLOADS</u>		
SUBSPANL	WAVESTRNG	AEROPANL	<u>FORCEMOM</u>	<u>MATINDEX</u>
CGTORIB		MACHNO	AEROPANL	PADTYPE
RIBTORIB	<u>VIBAC (WING)</u>	ALPHA	MACHNO	SIPTHCK
CGTOLE	TILESIZE	SHOCKJUMP	TILETHCK	PROOF
NODEFORDR	ONOFFRIB	SEPARJUMP	BLTHCK	MATNO
CGX1	FLTCOED	AEROGRX	XSL	
CGY1	TILETHCK	AEROGRY	FORCEZ	<u>MATCURVE</u>
TILETHCK	MACHNO	ABSHKCPRMS	MOMENTY	
SIPTHCK	GPEAK	ABSEPCPRMS		MATNO
TILEDENS	DISPL	REFPRESS	<u>STRS4 - 24 - 1</u>	DISPL
				STRESS
<u>XYZO</u>	<u>VIBAC (FUSL)</u>	<u>SUBPANL</u>	PARTNO	
PARTNO	VIBPANL1	SUBSPANL	LDCASE	
DRAWNO	VIBPANL2	X1	MACHNO	
IMLOML	FROMFRAME	Y1	STRESSMX	
XLOCAL	FROMCL	Z1	ACTPROOF	
YLOCAL	MACHNO	-	SRATIO	
ZLOCAL	GPEAK	-		
TRANSF	DISPL	-		
XORBITER	SPAN	X4		
YORBITER		Y4		
ZORBITER		Z4		

Fig. 7 Schema for all data used in Orbiter tile analysis.

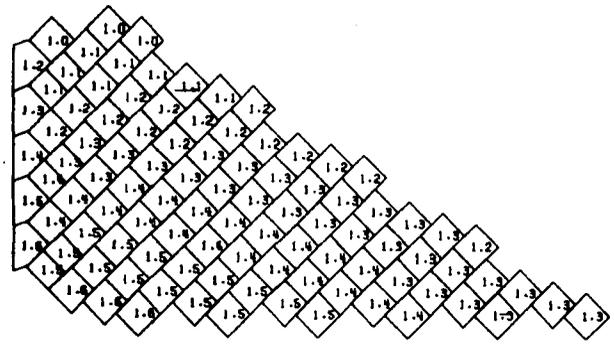


Fig. 8 Thicknesses of selected tiles in aerodynamic panel number 3.

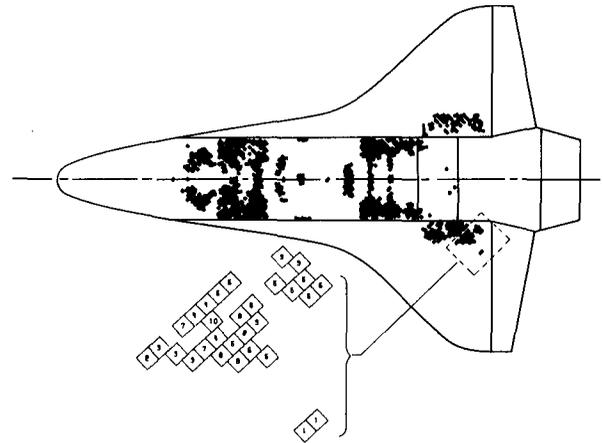


Fig. 9 Priority groupings of calculated stress divided by proof stress for undensified tiles (1 most critical).

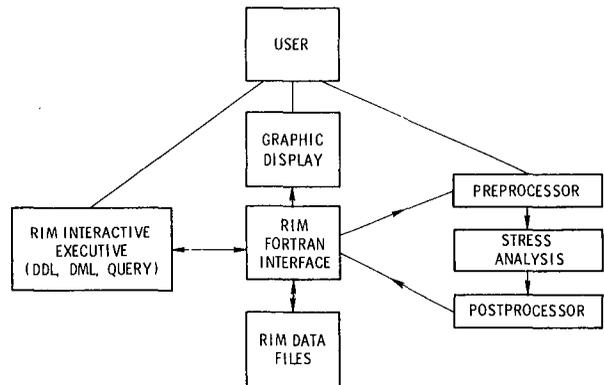


Fig. 10 Automated data management/analysis system for Orbiter tiles.



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16. Abstract This paper demonstrates the use of an engineering data management system to facilitate the extensive stress analyses of the Space Shuttle Orbiter thermal protection system. Descriptions are given of the approach and methods used (1) to gather, organize, and store the data, (2) to query data interactively, (3) to generate graphic displays of the data, and (4) to access, transform, and prepare the data for input to a stress analysis program. The relational information management system was found to be well suited to the tile analysis problem because information related to many separate tiles could be accessed individually from a data base having a natural organization from an engineering viewpoint. The flexible user features of the system facilitated changes in data content and organization which occurred during the development and refinement of the tile analysis procedure. Additionally, the query language supported retrieval of data to satisfy a variety of user-specified conditions.					
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