THE DEVELOPMENT AND USE OF A MATERIALS DATABASE FOR PRODUCT DESIGN AND COMPONENT LIFING.

Barry J Piearcey, Chris K Bullough, Martin Hughes and Steven J Moss

ALSTOM Energy Technology Centre, Whetstone, Leicester, U.K.
Tel. +44 116 201 5657, e-mail barry.piearcey@energy.alstom.com

ABSTRACT

Tremendous progress has been achieved in the application of finite element analysis techniques for the modelling of the behaviour of components and structures but the success of application is often limited by the availability of appropriate materials design data. Even when data are available, usually from published sources, some of the supporting metadata is often missing and validation of the design data is not possible. Even well planned characterisation of materials properties through well executed testing programmes lose their value as details of the test parameters and materials are inadequately recorded; and ad-hoc statistical assessment methods obscure the true minimum properties of a material.

This paper describes the development and structure of an MSC/MVISION materials database which is designed to store test and design data. Metadata has been defined to describe each material product and property precisely, standard methods of data analysis provide validated design data and each datum is allotted a quality value. Examples are included which illustrate how the data are used for statistical process control, thermal analysis, stress analysis and the prediction of component life using a continuum damage approach.

The similarity in the technologies used for these disparate activities is counterbalanced by the lack of material property data of sufficient quality. This situation is recognised world-wide as is the inability of any single company to justify adequate resource to correct it. It is concluded that the high cost of producing high quality material product data by independent testing calls for more facilities for the assessment, reporting and exchange of data within MSC/MVISION and highlights the need to agree an international schema and glossary of terms for data exchange.

Introduction

We live in a world which has been created by reference to a knowledge of the performance of material products. Man’s natural competitive spirit has led to his assessment of the materials available to build more secure and comfortable housing, better weapons, tools to manufacture labour saving aids for the production of foodstuffs and vehicles for the transport of his family, his possessions and the products necessary to his life in society. Traditionally we have judged the performance of these products by comparison of their performance within a specific environment but the cost of this historical pattern of component testing has often proved to be as high as the loss of life itself. Life in the new millennium will begin with a great advantage because the performance of new products can now be modelled before production is contemplated, the degree of confidence in their performance can be assessed and their successful performance assured, the concept of “failure” within a prescribed lifetime being replaced by the concept of “risk factor”. Preparation for this vision of utopia has begun and it is our responsibility to ensure that it is built on firm foundations, in particular, easy access to appropriate materials information.

In this paper, we have noted the materials data required at each step in a typical component modelling process, defined the material testing required and described the need for the subsequent materials data assessment.

1. Modelling the behaviour of components and structures

The technology used to model the behaviour and performance of components and structures is now well established, albeit in continuous development. These tools have been designed to call on specific materials data for thermal and elastic analysis but more sophisticated techniques are now being used for inelastic analysis which introduce the concept of time or cycle dependent properties. Thus the range of material properties required has been extended and more forward planning is required if the modelling is to be successful. In the following, the data required for each step in the modelling process are summarised.

1.1 Preliminary materials selection and data audit

Structural analysis is often used at the two extremes of the design process, at the end, to explain why the design and/or the material selected did not perform as expected; but more often now, at the beginning, to adjust the design to meet a required service life. In both cases, it is necessary to plan ahead to ensure that the appropriate data are available and representative of the candidate material chosen. As each analysis is performed, the precise data for each material product can be accessed and used directly from the database. At ALSTOM, the process of materials selection is approved by the Materials Function leaving the designer the flexibility to select from a list of candidate materials approved for use for a particular class of product.

1.2 Thermal Analysis

The failure to consider the effect of temperature on material properties, often as a function of time, could be catalogued by the numerous examples of structural disasters recorded in the last fifty years, from the brittle failure of welded ships to the loss of airframe sections of certain passenger carrying aircraft. Many of the material products used in the aerospace industry are subjected to cyclic changes in temperature over ranges of 150°C in subsonic airframes, over 500°C in supersonic and space vehicles and over 1000°C in gas-turbine and rocket engines. Thermal gradients in components lead to distortion, loss of goodness of fit and stresses and strains which cannot be accommodated. Thermal analysis of a component is often our first consideration in the design of gas-turbine components, simply because of the severe thermal cycle and the need for dimensional control. To illustrate the diversity of property needs, the analysis of a turbine blade is used for illustration.

1.2.1 The model and input data

Figure 1a shows a meshed model of a turbine blade and the temperature distribution through the component at a particular time in its cyclic use. The model was developed from the CAD description of the component at temperature. Figure 1b shows the variation of temperature as a function of time. The calculated temperatures provide a measure of the structural distortion to be expected in service and are used to compute thermal strains for lifing purposes.

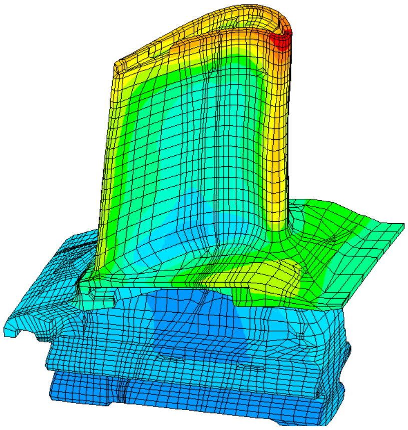


Figure 1a.Temperature distribution within a turbine blade

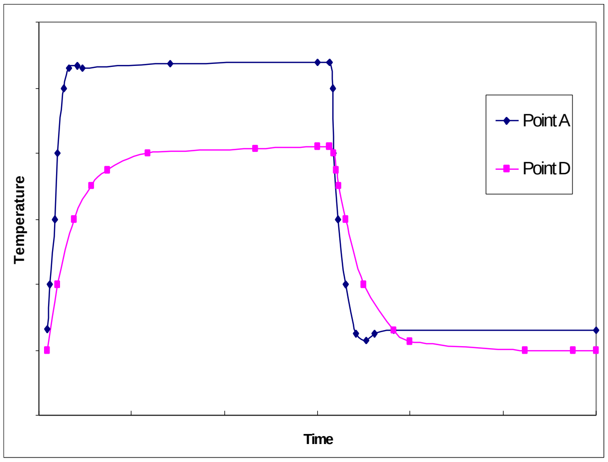


Figure 1b.Variation of temperature with time in a turbine blade at two nodes during a load cycle.

The temperature distribution varies as a function of time and this is illustrated in Figure 1b, where the temperatures of two blade positions are plotted with respect to key stages in the operating cycle. These data provide <INPUT1> to the Life Assessment System which is designed to test whether any element has exceeded the design criteria defined by the material property data.

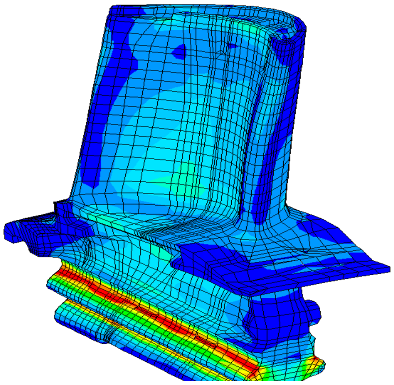
1.2.2 The data required

The heat transfer analysis for the blade relies heavily on input data from the aero-thermal calculations, these describe the pressure, temperature and velocity distributions of the hot gas and secondary air flows for cooling purposes. Heat transfer through radiation, conduction and, where necessary, convection are addressed in the analysis of the system, which includes gas flows and the influence of contacting and neighbouring parts of the turbine. From a materials standpoint, the properties required for thermal analysis are physical in nature (e.g. conductivity, emissivity, etc.) and these are added to the Summary of properties recorded in Table 1. However, guidelines established by the concept design and preliminary materials selection may recommend a maximum continuous operating temperature and set limits to the environmental life of the component with respect to corrosion of the blade material and/or its protective coating. These are compared with the model and a preliminary adjustment to the volume of cooling air or dimensions may be necessary to meet these criteria.

1.3 Structural analysis (elastic)

Since the constraints on mesh design are much greater for structural analysis than thermal analysis, the mesh for the latter is prepared with the former in mind. Thus a single model is used for the thermal and elastic analyses. It should be noted, however, that further mesh refinement is often necessary for any inelastic structural calculations. From the thermal analysis, temperatures are available throughout the operating cycle. Using these temperatures along with the centrifugal load and pressures exerted by the gas streams at corresponding cycle times, the elastic stresses throughout operation are calculated. Figure 2a shows the model and the stress distribution through the component at a particular time in its cyclic use.

Figure 2b shows the variation of stress as a function of time at two locations in the airfoil. Note that, in spite of the centrifugal force, the longitudinal stress at one location is in compression, a result of the thermal gradient.



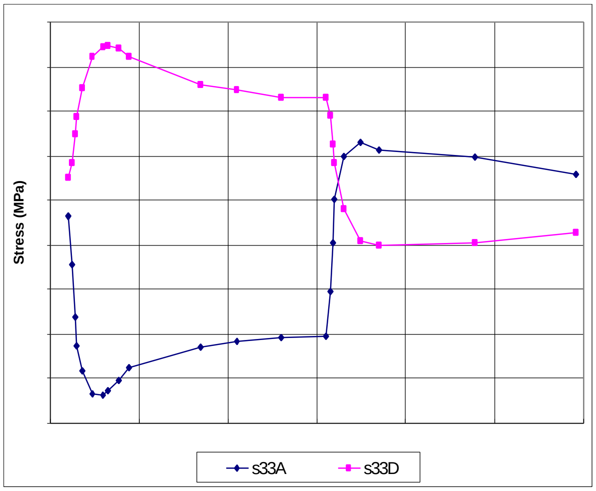


Figure 2a.Stress distribution within a turbine blade

Figure 2b.Variation of stress with time in a turbine blade at two nodes during a load cycle.

1.3.1 The data required

Another assessment can now be made of the conditions of stress and temperature at each node which relates to the monotonic tensile strength values of the candidate materials and the criteria established for preliminary design. Factors to account for ‘over speed’ criteria must also be included because of such a possibility in a gas turbine engine. Elastic modulus, tensile, creep-rupture properties and time to amount of creep strain are required at this stage. These data provide <INPUT2> to the Life Assessment System.

1.4 Vibration analysis

Vibration in any component can be expected to lead to its failure by fatigue if the mean and cyclic stresses exceed particular values. A turbine blade vibrates over a range of frequencies and the designer uses his skill to ensure that its natural frequency is avoided for all but the briefest of times. Figure 3a shows the stress distribution through the component in vibration at the extremes of its deflection. Figure 2b shows a representation of fatigue and tensile data in the form of a Goodman/Gerber diagram at the temperatures of three locations in the blade compared with the stress. The data illustrated have not yet been corrected for the effect of creep, indicated by the inflection of the high temperature curves. These data provide <INPUT3> to the Life Assessment System.

1.4.1 The data required

The usual way of representing high cycle fatigue data is by a Goodman or Gerber diagram which combines fatigue strength (stress to produce failure in 10^8 cycles at various stress ratios) with tensile and stress rupture values. The criteria for maximum mean stress varies between companies and application but 90% of the typical 0.2% proof stress or the stress to produce rupture in 1000 hours, whichever is the lower, is common. A separate assessment of the creep life is always made but fatigue /creep interaction can be more damaging requiring additional data to address this area.

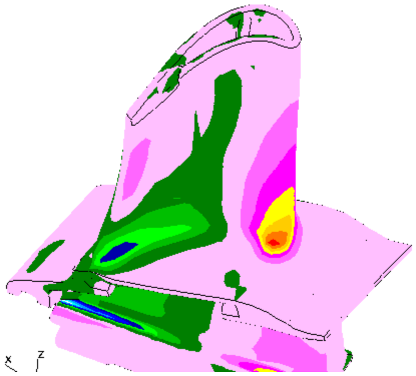


Figure 3a.Stress distribution within a turbine blade in vibration at maximum deflection

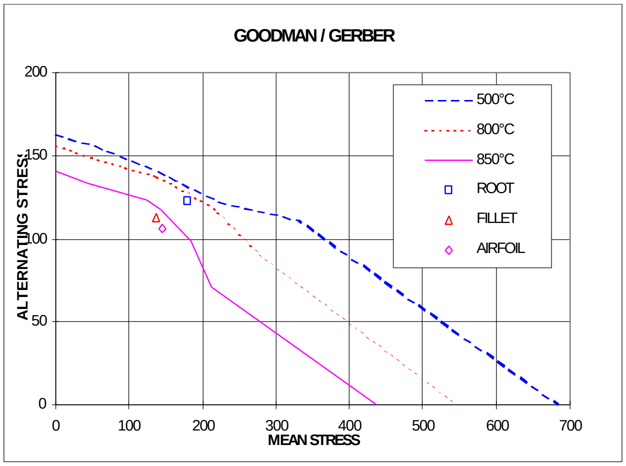


Figure 3b.Comparison of stress in component with properties of candidate material at locations of interest

1.5 *Structural analysis using simplified methods*

A range of simplified methods account for material non-linearities (creep and plasticity) without moving to a full FE-based inelastic computation. These simplified methods use the stresses from the elastic structural calculations along with the corresponding temperatures. A strain-based low cycle fatigue calculation is used here to illustrate the role played by simplified methods and the material data needed. Where the assessment of the elastic results demonstrate that the stress at some locations exceeds the 'yield stress' or a particular proof stress, this local stress will be accommodated by plastic deformation, the extent of which is calculated by means of a 'Neuber correction'

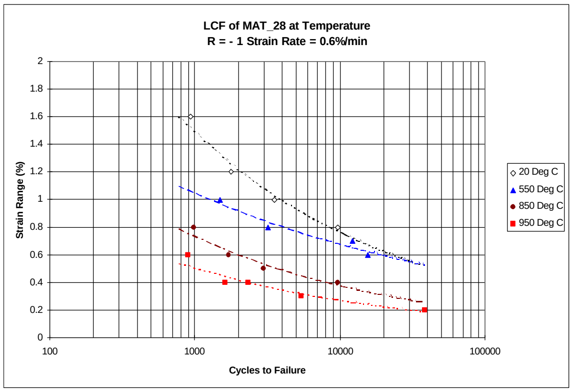


Figure 4a.Effect of strain range on life in a strain controlled fatigue test

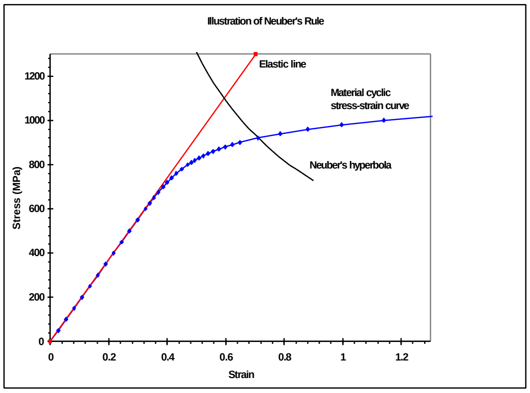


Figure 4b.Cyclic stress-strain curve and Neuber correction.

1.5.1 The data required

Experience has shown that all materials have a limited strain tolerance which can be illustrated by strain-controlled fatigue testing to generate cyclic stress-strain curves over a range of temperature. The effect of strain amplitude on the life of a particular material is illustrated in Figure 4a and a generic cyclic stress-strain curve in Figure4b. These data provide <INPUT4> to the Life Assessment System.

1.6 Summary of the data required

The materials product data identified by the thermal, vibration and structural analyses are summarised in Table 1 as follows.

Analysis	Material	Property	Variation with:
Thermal analysis and cooling design	Turbine blade alloy Blade Coatings	Max. continuous operating temperature Environmental life limits Specific heat capacity Thermal conductivity Thermal expansion coefficient Emissivity	Temperature Time
Structural analysis (elastic)	Turbine blade alloy	Density Dynamic modulus of elasticity Minimum tensile strength Creep rupture strength to 10,000 hours and time to % creep strain	Temperature Time
Vibration analysis	Turbine blade alloy	High cycle fatigue strength (~100Hz) (load controlled)	Temperature Stress ratio Cycles
Structural analysis simplified methods	Turbine blade alloy Blade Coatings	Low cycle fatigue strength (strain controlled), Relaxation data, time to % creep strain or rupture, stress-strain curves	Temperature Strain ratio Cycles Time

Table 1. Summary of material properties called up in thermal, structural and vibration analyses

2. Lifing assessment

2.1 Structural analysis

The turbine blade is a rotating component and is free to extend as a function of time. There are two factors which limit its life, the first is excessive extension due to creep which may cause excessive wear or damage to the tip or shroud and the second, cracking leading to fracture, possibly accelerated by vibration. The first lifing assessment assumes that the preliminary design criteria have been met with regard to stress limit and vibration and can conclude that its performance will apparently meet the design intent. However, use of the thermal, fatigue and structural analyses in conjunction with the cyclic stress strain variation throughout the cycle enables time and cycle dependent strains to be computed and assessed against the tensile, HCF, creep rupture or % creep strain and strain controlled fatigue data for each element in the model. Within ALSTOM, this process has been automated within our Life Assessment Software (LAS) which is integrated with the PATRAN environment as is illustrated by Figure 5.

This first pass, using LAS, will indicate the locations within the blade which fail to meet the design intent. There are several solutions to this problem, either, reduce the stress by changing the dimensions of the component and continue to iterate, or, reduce the temperature of the critical location, or, change the material.

This method has served the industry well in the past but the drive to improve efficiency, reduce the cost of ownership and enhance reliability of OEM products has put downward pressure on safety factors. In order not to increase the likelihood of failure, the reduction in safety factors has been accompanied by advancements in analysis complexity and accuracy. In the field of structural analysis, this has meant the routine use of detailed inelastic analysis upon which life assessment is performed.

<INPUT 1> T (f(x,y,t))

<INPUT 2> σ (f(x,y,t)

<INPUT 3> $\Delta\sigma,\sigma_{mean}$, T

<INPUT 4> Materials Data

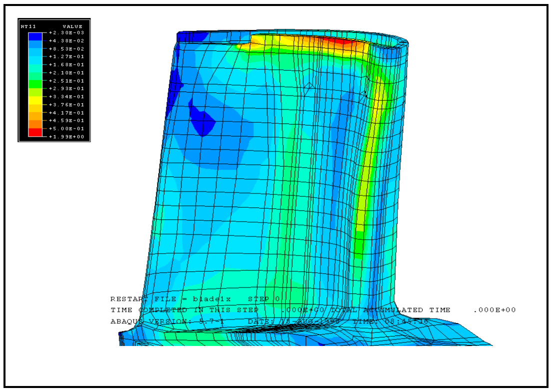


Figure 5a. Input to Life Assessment System

Figure 5b.Computed life of each element

2.2 *Inelastic based analysis*

The basis of this concept is that strain accumulates in accordance with the actual deformation characteristics of a material. A thermal and structural analysis is carried out as previously indicated, including the consideration of inelastic deformation due to creep and plasticity based on simplified methods. However, this time, the software computes, for each element, the cumulative strain due to creep and plasticity throughout the load history. The computation continues until the predetermined number of cycles is completed, a reliably extrapolatable steady cyclic response is achieved or a measure, such as creep strain, exceeds a predetermined value.

<INPUT 1> T (f(x,y,t))

<INPUT 2> σ (f(x,y,t))

<INPUT 3> $\Delta\sigma,\sigma_{mean}$, T

<INPUT 4> Materials Data

<INPUT 5> ε (f(x,y,t)) including creep and plastic components

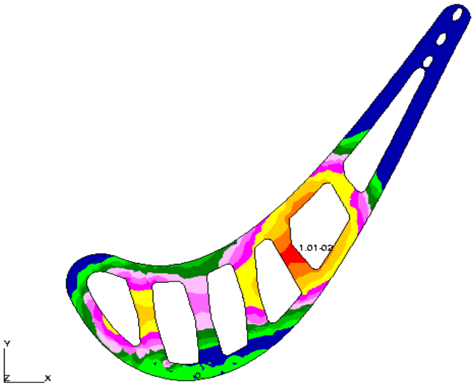


Figure 6a. Input to Life Assessment System

Figure 6b.Cumulative creep damage at each element demonstrates proportion of life used

2.3 *Iteration*

The result shown in Figure 6b may still give cause for concern if the life fraction approaches or exceeds unity. For example, a cooling passage may need attention or redesign. Following a design change the entire process is iterated until the life requirement is met, the safety factors are known and the performance is acceptable from a design perspective.

3. Materials data and data flow

The foregoing has defined the broad range of material properties required in the analysis of a component. Traditionally, these data were assembled by analysts in personal files and data compilations which included manufacturers data, in-house test results and reports of collaborative test programmes. It was found that the values of a particular datum depended on the source of data and the method of data analysis resulting in two or more engineers using different design values.

3.1 Data flow

A thorough analysis of this problem was carried out at ALSTOM (Piearcey and Bullough [1]) resulting in a better understanding of the flow of materials data and the definition of a basis for the development of a materials database. As each source of data was identified, it was added to the bibliographic database and the data transferred to an assessment file bearing the common name of the material and sub-divided by property. Experience has shown that the variation of many properties of materials with an independent variable (such as temperature) is similar for related material products. If that variance can be normalised, less testing of batches of material of a specific identity can provide reliable design data.

3.2 Data requirements

It became clear that the requirements of an acceptable database should include particular features, e.g.,

1. design values could only be ascribed to ‘a uniquely defined material product’
2. separate databases were required for test results and design data
3. the source of each datum should be recorded in a bibliographic database
4. standard methods of data assessment and analysis were required for both test data and the derivation of design data
5. a measure of the quality of each design datum was required
6. a Glossary of Terms should be associated with the database
7. An archive database is required to maintain copies of data replaced by those with superior quality.
8. the ability to exchange data between formats and locations was required.

The range of data and information used and its flow through the system is summarised in Figure 7.

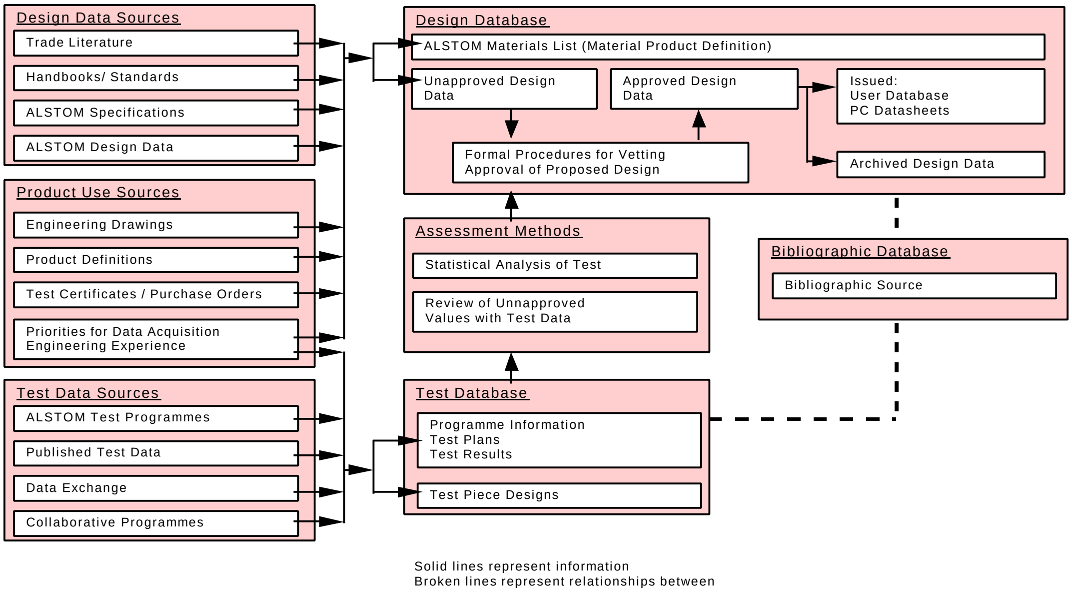


Figure 7. The flow of materials data

3.3 *Database design*

Concern may be expressed that the method of assessment of test data may vary between Materials Engineers or organisations. An assessment of creep rupture data carried out by Bullough [2] showed that, providing the method was controlled, different predictive models could be used or combined. In particular, the data analyses require that the resulting design data are defined by appropriate ‘metadata’ , one of the most important being the values of a qualifier called BASIS, an attribute which usually has the values ‘typical’, ‘minimum’ or ‘maximum’. It is, therefore, necessary that the appropriate value is defined by the analysts in their request for data.

Each attribute used to describe both material and property is included in a ‘Glossary of Terms’ associated with the database. This concept allows the definition of a ‘uniquely defined property’ which can be assigned to the ‘uniquely defined material product’ thereby ensuring that two analysts working independently within the company use precisely the same data.

This study provided the basis of a ‘schema’, the database design, where the attributes necessary for the definition of a material product and every property and its dependent and independent variables are recorded together with figure relations to enable the graphical representation of the data. In addition, the requirement to define anisotropy in material products has been assimilated, even to take into account the crystallographic orientation of single crystal components in relation to the test direction. The types of data are briefly described in Table 2.

Database	**Key to content**	**Type of data**
Test Database	test number	material product reference, test identity, location and orientation of test bar within the material product, test method
	type of test	values of attributes to describe a unique test raw test data in text files, processed data, tabular and graphical values, function coefficients
Design Database	Unique Material Number Product Specification	Composition, form, thermo-mechanical history
	Design property and property environment	BASIS of data and attributes relevant to the property type. Tabular and graphical values, function coefficients, interpolated and extrapolated values, variance
	Design use & limitations	surface condition, ruling section, associated specifications (quality & test)
Bibliographic Database	Source and date of publication	location and type of document
	Type of data contained	test data, typical design curves, security of data

Table 2. List of types of attribute.

4. Database Application

4.1 Mapping to PATRAN and FE solvers

The data requirements for structural analysis have defined specific property relations and their basis which are related to specific material products which may be anisotropic. The data, stored in an MSC/MVISION database can now be used by FE solvers or directly from within MSC/PATRAN when the database attributes have been mapped to the property names and modifiers used by the FE software. This exercise allows the use of MSC/MVISION's materials selector allowing rapid access to the data on-line. ALSTOM use a simple material number to define the material product which is precisely defined in a 'List of Materials'. All data associated with each material is version controlled and early versions of any data set are archived in case the results of previous analyses need to be compared with later ones in which any part of the data has changed. Other applications for the database include the processes of analysis, verification, validation and approval which have raised the requirement for data transfer, particularly to PC software. ALSTOM use Microsoft EXCEL extensively and have developed their own 'PC database client server' This tool is a combination of a compiled Visual Basic macro within EXCEL (the "client") and a compiled C program running under the Unix (the "server"). The passing of data between programs is achieved using a common network directory. Within EXCEL, the database "client" is used to select a database, prepare a query and define the dataset required. A tab delimited file containing this information is deposited in the common network area and , running in the background, the database "server" C program reads the file and submits it to the database via the MSC/MVISION 'database programmatic interface' (DPI). The 'DPI' processes the query, returns the result to the database "server", which formats the data, returning it to the common network area. Within EXCEL, the database "client" reads the file, and formats it for further use.

Many of elements of the ALSTOM Materials Database, illustrated in Figure 8, use EXCEL and it would be useful if more of these services could be provided within MSC/MVISION On the other hand, the ability to transfer data from MSC/MVISION to other software products, without loss of any data, is highly valued and facilitates the use of lower cost PCs by many users.

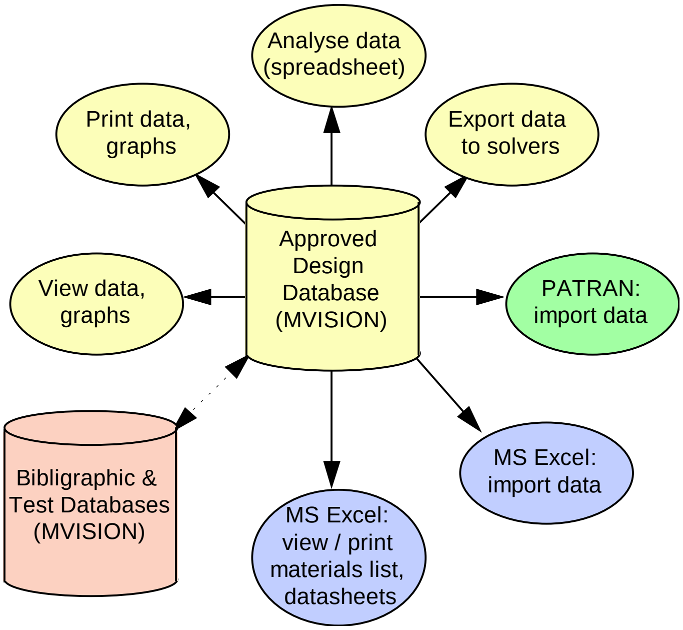


Figure 8. Elements of the ALSTOM Materials Database.

4.2 Extending the database application and use

The urgent need to establish a single source of data for designers and analysts has brought the benefits of rapid access to machine readable and auditable data and the conservation of resource in a busy environment. Very soon, the same benefits were required for other types of material product and related technologies were requested and databases for combustion technology, diesel engine, turbochargers and electrical machines are in development. A new benefit resulting from the launch of the ALSTOM Materials Database is now being realised for the purposes of process control.

4.3 Statistical process control

Although all available test data at a point in time are used in the derivation of design data, the mean values of production test release certification and their variance are used for comparison with ongoing release tests from each supplier. These data are increasingly provided electronically and rapid proof of conformance and trend can be brought to the attention of the control laboratory. All data are logged in the Test Database and the processed values from each test are plotted together with the current typical, minimum and maximum specification values. An example is shown in Figure 9 showing the variance of tensile strength as a function of test date. The graphs point very quickly to any disturbing trend or supplier even though the product may be conforming.

The data, being well populated, can also be used to provide fixed points in the analysis of a property relation such as Ultimate Tensile Strength vs. Temperature, and the variance used proportionally in the determination of ‘minimum design values’. Since the data used and compared are located in separate databases, ALSTOM find it convenient to export the data into EXCEL spreadsheets for analysis and graphical display.

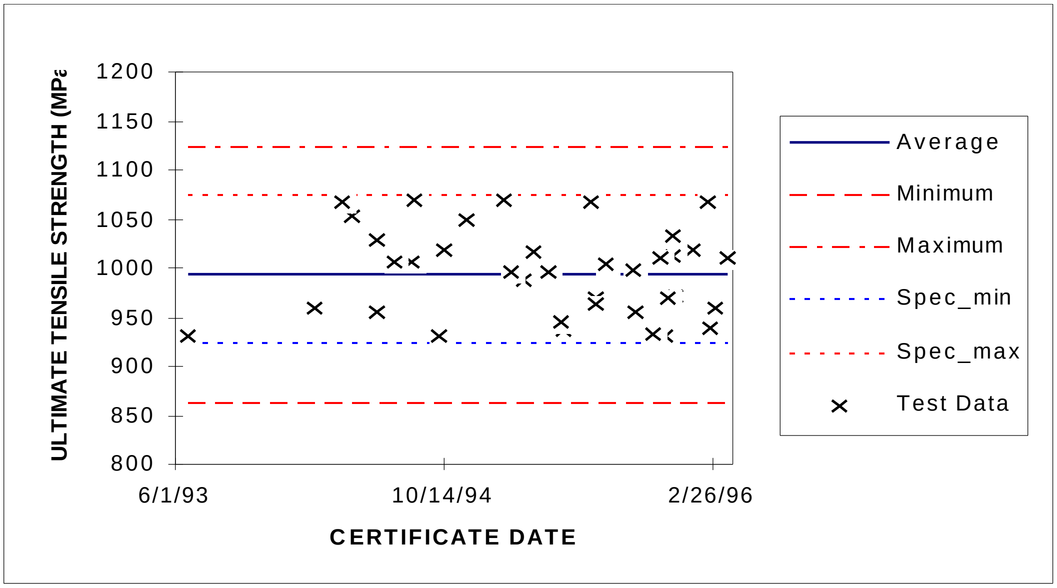


Figure 9. Statistical Process Control of material product incorporated into materials database.

5. Discussion

The ALSTOM experience of building a materials database to satisfy the requirements of designers and analysts using MSC/MVISION is generally considered to have been very successful. The database design required approximately ten man-years development but several advantages of the implementation have been realised, they include,

- easy addition of new attributes and figure relations
- easy to export data and incorporate in other formats
- rapid dissemination via file transfer to mirrored sites
- widely used and accepted
- rationalised data gathering and data responsibilities resulted
- better quality assurance.

On the other hand, certain difficulties have been experienced which require further software development or internal resource, these include,

- the facilities for the customised printing of a data set are too limited, ALSTOM use EXCEL workbooks for data approval as well as for use by engineers without workstation facilities
- the current single precision database is insufficient for many data model coefficients
- disparate data sources use different schemas and attributes making reliable data exchange uncertain and time consuming
- the development of custom databases by new users is not easy, requiring strict training and detailed instructions
- increasing requirement for intranet access.

One of the features extolled for MSC/MVISION has been its flexibility to allow a wide range of schemas and attribute names, now demonstrated by the disparate features of the MSC/MVISION Databanks. Among users, this has also led to inefficient hierarchies and relations, for example, by making it difficult to compare the properties of different classes of material product. The authors believe that the concept of an ‘international schema’ for materials product data should be implemented to ensure that data can be exchanged without the delays of interpretation and mapping files. ALSTOM have formed their own database club to develop this idea, sharing their database design, associated files and procedures with external companies on a cost sharing basis. It has enable one company to implement a database system within three months, which is currently being populated. Ironically, it is perhaps the most attractive features of MSC/MVISION, namely its flexibility and ease of implementation, which are countered by the user community's long-term need for a single, stable and well understood schema in each area of industrial application. It is essential that a database of the properties of material products is based on a 'uniquely defined property' as well as a 'uniquely defined material product'.

6. Conclusions

Finite element software is regularly used at ALSTOM for thermal, elastic, vibration and inelastic analysis of gas turbine components. The need for material product data and its properties has been satisfied by an MSC/MVISION database which can be accessed from within the MSC/PATRAN environment. New Life Assessment Software has been developed based on a continuum damage mechanics approach and is being used to predict the life of components at the design stage.

The high cost of producing high quality material product data by independent testing calls for more facilities for the assessment, reporting and exchange of data within MSC/MVISION and highlights the need to agree an international schema and glossary of terms for data exchange.

7. Acknowledgements

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8. References

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[1] Bullough and Piearcey, "An on-line materials database for the design of gas turbine components", ASME Paper No. 97-GT-167, June 1997.

[2] C K Bullough, Transactions of the ASME, Vol. 120, No. 3, p. 588. July 1998.