STRUCTURAL ANALYSIS FOR THE 21ST CENTURY

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ABSTRACT

Structural analysis tools have progressed to a stage where they are increasingly used in everyday engineering applications.

Within the aircraft industry, the application has mainly concentrated on providing an insight into both detail and overall structural behaviour and to aid design decisions via optimisation. The testing of structures still forms a large part of the design and qualification process, with analysis providing additional information to support these activities.

We are now moving to an era where detailed simulation of a structure is required, such that testing programmes can be significantly reduced. To meet this requirement, results must be produced with extremely high levels of confidence and shown to be representative of the real structure.

This paper considers some of the current capabilities and future developments in analysis technology which will be required to move towards this environment of full simulation, and also considers some of the associated problems and risks.

Introduction

Structural analysis tools have been improving steadily over several decades. They have progressively encompassed a wider range of engineering problems whilst at the same time have also become more user friendly. Much of this progress is attributable to the dramatic improvements in computing hardware performance, which has enabled the time to perform a structural analysis to reduce, whilst the size and complexity of the theoretical models has increased. The software has also advanced, bringing realistic analysis and visualisation of these complex problems to the engineer's desk.

In the aircraft industry structural analysis tools, such as MSC/NASTRAN [1], have been used for nearly thirty years, providing an insight into the behaviour of structures at both full aircraft and at detail component level. However, the analysis has, in general, been used to aid understanding of structural behaviour and to provide a basis for optimum design decisions. A large part of the design and qualification process therefore has relied on extensive testing to validate the decisions made and to ensure the structure has been qualified to meet its design requirements. However, it should be noted that even the testing activities have indirectly involved significant structural analysis and theoretical calculations.

Clearly there is potential to significantly reduce the amount of testing performed, and reduce its associated high costs, if an adequate simulation of the structure can be performed. Adequate, in this context, means with sufficient confidence that the results are as good as, if not better than, the equivalent test. To meet this, results must be produced with extremely high levels of confidence and shown to be representative of the real structure [Fig. 1].

The current simulation capabilities and future developments are considered here along with the associated implications, problems and risks.

Structural Analysis Today

The use of finite element analysis in structures ranges from analysis of complete aircraft models [Fig. 2] to small local details. The objective of these analyses being to understand the internal load distribution caused by the external environment. These internal load distributions are often used in further detailed stress analysis calculations to provide a detailed model of the structural behaviour. This information is then used to make a judgement of the effect on the structural integrity of the part in question. The types of analyses performed encompass both static and dynamic, linear and non-linear. The applied loading for these types of analyses is, in many cases, also derived theoretically rather than from measured data. For example, aerodynamic panel methods and computational fluid dynamics (CFD) may be used to provide external pressure loading [Fig. 3], and thermal analysis may be used to calculate a temperature distribution.

Thus, to completely design and analyse the structural performance of an aircraft structure, by theoretical means, is possible. However, the confidence that any theoretical model is representative of the real structure varies greatly, depending upon the amount of supporting evidence and experience of the particular modelling application. If a design was produced and qualified by analysis alone then it is likely that larger safety factors would have to be applied to ensure conservatism. This would be counterproductive for the aircraft industry where structural weight is critical to performance and cost.

The extent to which theoretical analysis models are used currently gives an indication of the level of confidence in these models.

Initially, at concept stage, structural layouts can be sized using coarse analysis models and optimisation tools such as ECLIPSE [2], an "in house" BAe program, which provides a minimum mass optimum solution to meet aerodynamic, strength, performance and manufacturing requirements. This concept phase is almost entirely based on analysis and theoretical predictions, and is considered acceptable for the level of detail available at the early project stage.

At the detail design stage tools such as MSC/NASTRAN are used to determine the overall load distribution throughout the aircraft. MSC/NASTRAN is also used at detail component level to investigate local design solutions. During this design phase, in addition to extensive calculation, testing may be performed in order to provide further evidence of an acceptable design solution. The whole process is aimed at providing confidence that the design solution meets its requirements. Generally, the test evidence in this phase is required to assess new material properties and to investigate novel construction methods.

This highlights the fact that testing is the only reliable method of producing material properties. It also shows the need for caution when using analysis tools outside the limits of current experience. The analysis is only considered acceptable if it is validated, by having been compared with a test for the same type of problem.

In the qualification phase of the design, the objective is to show that a structure is fit for its intended purpose. This may mean that it must never fail in service, but equally it could be designed to fail under given conditions, as in the case of a weak link designed to fail in order to protect other more significant structures. Additionally, for any part, the acceptable level of risk associated with it will vary depending upon how critical it is to the safe operation of the aircraft. Consequently, there is no simple definition of what is acceptable or unacceptable that can be applied to all parts. The structural qualification of any part consists of providing sufficient evidence that the design does meet its purpose, and this evidence may take a variety of forms including both test and structural analysis [3].

The major structural tests form the core of this qualification process [Fig. 4], with a range of components and airframe tested both statically and for fatigue. Structural analysis and detail stress calculations are also performed, to check the final design, and to provide calculated evidence of the structural integrity of the aircraft. These check stress calculations are then compared with the test results, in order to validate the check stress methods [4].

Another area where finite element techniques are used is in the simulation of manufacturing processes. Simulations of the forming process are performed to help with tool design [Fig. 5] and to optimise applied pressure and temperature loading cycles. The use of these analyses are usually in conjunction with the manufacture of trial components, but nevertheless give valuable additional information which is not available from a single expensive manufacturing trial.

The above discussion highlights that analysis capabilities exist for a wide variety of topics, but analysis in isolation is not considered to be sufficient for the majority of today's problems.

Structural Analysis and Testing

The advantages of simulation over testing are quite substantial. To create an analysis of a given structure is far cheaper in most cases than creating a test. Creation of test rigs, manufacture of the component and the addition of instrumentation are all costly activities. Having invested money in a test it is generally used once and if it fails prematurely or in an unexpected manner it may be of limited use. Results are available only where the instrumentation has been placed which therefore limits the amount of useful information available. An analysis, however, once created gives additional information and understanding on any part of the structure. It is repeatable at minimal extra cost, and modifications can be introduced to gain further understanding of the sensitivity to any feature. The only disadvantage is that analysis results are considered to be less representative of the real structure than an equivalent test.

If full simulation is to become a reality then structural analysis techniques must be able to provide at least as much reliable information as the equivalent tests. Therefore, it is worth considering how representative tests are at present and to what extent they already rely on structural analysis techniques.

Tests are a physical representation of the real structure with its associated loading and environment. In most cases the structure is fully representative, in that the real structure can be placed in the test rig. However, some modifications are often required in order to introduce loads or place instrumentation on the structure. The effects of these modifications are usually assessed using theoretical techniques including finite element analysis.

It is not always possible to apply the real loads to a test. For example, an aerodynamic pressure load is likely to be applied via a discrete number of loading pads, which attempt to represent the real loading condition. The difference between discrete and continuous load application in this case is usually assessed through analysis, to ensure that the overall effect is acceptable. It is also unrealistic and expensive to apply large numbers of load conditions to a given test component, but thousands of load cases can be applied easily to an analysis [5]. Therefore, analysis is used to read across to the other load conditions not actually tested.

In a similar manner, the in-service environment may be difficult to reflect on a test. The vast majority of tests on large components and airframes are conducted at room temperature in dry conditions. The effects of a hot and wet environment which cannot be applied is therefore taken account of by reading across from smaller environmental tests and analysis work.

There is no single correct answer from any test. Variability in material properties, construction methods, dimensional tolerances and the environment will produce a different result if a test is repeated on batches of the same component. This is not a problem where the variability is relatively small and several tests are performed, as with material coupon tests. However, where only a single test is performed then it is impossible to know how representative that test is. In the case of full airframe tests, past experience, component box tests and finite element analysis have all contributed to giving confidence that the single test result is reliable. Differences between the test and the analysis are investigated and resolved to ensure the limitations are understood.

Testing in general is considered more representative than analysis because the real structure is used. However, the extent to which analysis is already a part of the testing process should not be underestimated.

In the past tests have revealed problems which have not been identified within the analysis. This has further reinforced the belief that testing is needed to reveal the unexpected problems. It should be remembered, however, that the converse is also true and that analysis has also revealed problems not detected by tests.

Future Developments

The above discussion has shown that some of the limitations of tests are already overcome using analysis. The following discusses some of the developments [Fig. 7] which may, in the future, lead to analysis taking on a much wider role encompassing more of the tasks performed on tests today.

Theoretical Basis

The whole principle of using analysis to simulate real structural behaviour relies on the theoretical methods being available to model the appropriate effects. The extensive research and development, being pursued throughout both industry and universities, will move the technology forward and enable greater understanding of more detailed problems. This will eventually become the underlying theory of tomorrow’s software.

Some areas of particular interest concern the dynamic effects on structures such as impact, vibration and acoustic effects. Not only are the effects of these phenomena difficult to model but in many cases the applied loading environment is also difficult to establish. The development of reliable theoretical methods, to predict both the loads and the effects, could lead to the elimination of many tests. Other areas which may lead to improved analysis concern the effects of local features, such as bolted joints, bonded joints, hole tolerances, contacts, defects and numerous other small scale features. Each of these effects form a major research topic in their own right, and can often only be analysed in isolation by making assumptions on boundary conditions [Fig 6]. However, the ability to introduce these small scale effects efficiently into a larger analysis would lead to a better representation of the real structure. Idealisation techniques are currently used to achieve this but the idealisation is a potential source of error.

Material Data

No matter how good the structural analysis theory, it will never produce reliable answers without the appropriate accurate material data being available. Whilst simple material properties are generally well known and accepted, as applications and materials develop there is an on-going need for more material data. Examples include strain rate dependent properties and damping properties for dynamic analyses, and failure properties of composites. These types of properties are inter-linked with the theoretical methods and, therefore, as the theory develops there is a demand for fundamental material properties to be derived. The majority of this data will have to be determined from tests and the variability of this data will be a limiting factor on how accurate any theoretical analysis can be.

Loading Data

The externally applied loading for any analysis needs to be known to a level of accuracy consistent with the analysis. Simulation of the loading environment is possible and developments in areas such as computational fluid dynamics may eventually lead to accurate application of aerodynamic loads without the need to use wind tunnel or flight test data. Again, the area of dynamic loads gives most problems, where it is particularly difficult to predict the magnitude of many types of dynamic loads which are semi-random in nature. Testing and measurement may be the only way to get an accurate understanding of external loading environments, but the prediction methods are improving steadily. It is appropriate to note that the external loading environment is not totally independent of the structure and as such a full multi-physics approach may be required to ensure the correct structure-fluid interaction.

User and Software Environment

In order to effectively utilise the developing methods, the software and hardware environment needs to be able to cope with the demands placed on it. Fortunately the performance of affordable computers is increasing rapidly, thus the potential to analyse structures of enormous complexity, considerably greater than today, will be a reality in a few years. It is essential that the software and methods are in place to exploit this.

This means delivering information, to the engineer, in a form that is readily accessible and can be easily understood. Visualisations such as real time animation are key to providing understanding but the data underlying the engineering performance of the structure must also be available. Automation of the whole process of creating and analysing structural models, and the use of expert systems, will help to eliminate the element of human error in the idealisation and interpretation process. The use of the computer to perform most of the mechanistic activities will leave the engineer free to perform the engineering checks and make the best use of the data being provided.

In terms of idealisation, it should be possible to model structures exactly as defined by the CAD geometry without the need to make gross assumptions or introduce further approximations. This may carry a high computing overhead for larger components, but this will become less important as computing power increases. The ability to create very complex models rapidly and incorporate non-linear effects at a local detail level will provide a realistic alternative to the current approximations using idealisation. The fewer the idealisation assumptions associated with the geometry, the fewer the opportunities to introduce errors.

Integration of all tools involved in the analysis processes is essential in order to provide direct access of data in any system. Integration allows rapid turn around of jobs without the problems associated with managing and transferring data. It should be noted that the geometry definition is central to the structural analysis activities and associated stressing tools and therefore the future analysis system is likely to be driven directly from the CAD system. However, the ability to interchange CAD systems, analysis systems and post-processing systems, within the whole analysis environment, is essential if collaboration with different partner companies is to be maintained. This flexibility is also desirable in order to incorporate new improved tools into the analysis environment, as the technology develops.

To summarise, the essential features of the future environment are automation, integration and visualisation. If analysis tools are available with these features inherent, on a very powerful computing platform, then the simulation capability will be an order of magnitude more reliable and easier to use than it is today.

Elimination of Errors at all Stages

The types of errors and uncertainties present in the analysis methods must be understood in order to minimise them. These are more formally addressed in documents such as the SAFESA Technical Manual [6] where a methodology of conducting any finite element analysis is proposed. Within this process identification, quantification and treatment of errors is required. Also, refinement of modelling is required in order to understand and reduce the critical contributions to the error.

This type of approach needs considerable effort to be expended on understanding the sensitivity of the model to the assumptions made, and re-analysing when necessary. Again, software automation of the mechanistic parts of this process will provide the basis for ensuring this process is followed without the introduction of further errors. The engineer is left with the decision of whether the magnitude of error present is within the acceptable bounds of risk.

The elimination of errors in the process is dependent on ensuring the quality of every part of the analysis process. This not only includes the quality of software, data and methods used but above all the quality of the engineer making the decisions.

Validation of Techniques

As an extension of the identification and understanding of errors described above, the experience gained from the past is essential. This is the main contributor to confidence in any new technique.

In order to utilise structural analysis more widely it is essential that the techniques are shown to be effective in predicting the real structural effects. This can only be achieved by extensive validation of any technique developed. Validation of a modelling technique is performed by comparison with test so that its application and limitations are fully understood. Validation must provide sufficient confidence in the application of a technique that any model of a similar type is considered to be as valid as an equivalent test.

The costs of the initial validation test must obviously be met, but the potential savings on future qualification tests are large. The emphasis here is to use tests to validate the analysis and then use the analysis to provide the qualification.

Conclusions

There are obvious weaknesses in the ability of analysis to accurately predict all structural behaviour, but it has been shown that tests also have deficiencies, and that a combination of analysis and test is already accepted as a way of providing the appropriate level of confidence in the structure.

With the likely improvements in hardware performance and the increasing sophistication of the theoretical methods, future software will undoubtedly be more efficient and representative than it is today.

The balance between test and analysis will move towards increasing analysis activities. The cost to perform analyses will reduce relative to the complexity of what can be analysed. The reducing costs coupled with more representative simulations will be powerful drivers towards reducing the amount of testing performed in the future.

The extent to which analysis will be used in the future qualification of structures will depend upon the confidence the engineering community has in its results. This confidence will only be built if errors throughout the process are eliminated. Automation of all aspects of the analysis process will contribute greatly by removing the scope for the user to introduce further errors. Validation will be the key to understanding the significance of any errors and thus determine the acceptability of the application of the analysis method.

There is still a long way to go before the level of confidence in analysis is as high as it is for a test. The development of structural analysis within the aircraft industry is clearly moving in the right direction.

Acknowledgements

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FIGURE 1 REAL AIRCRAFT IN FLIGHT

FIGURE 2   FINITE ELEMENT MODEL OF FULL AIRCRAFT

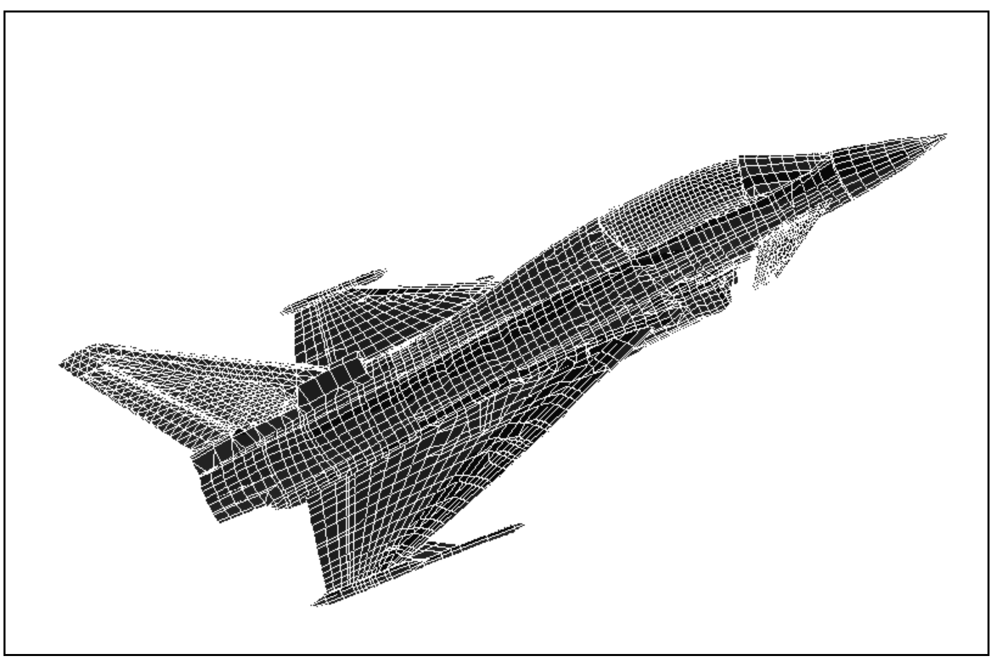


FIGURE 3   AERODYNAMIC PRESSURE DISTRIBUTION

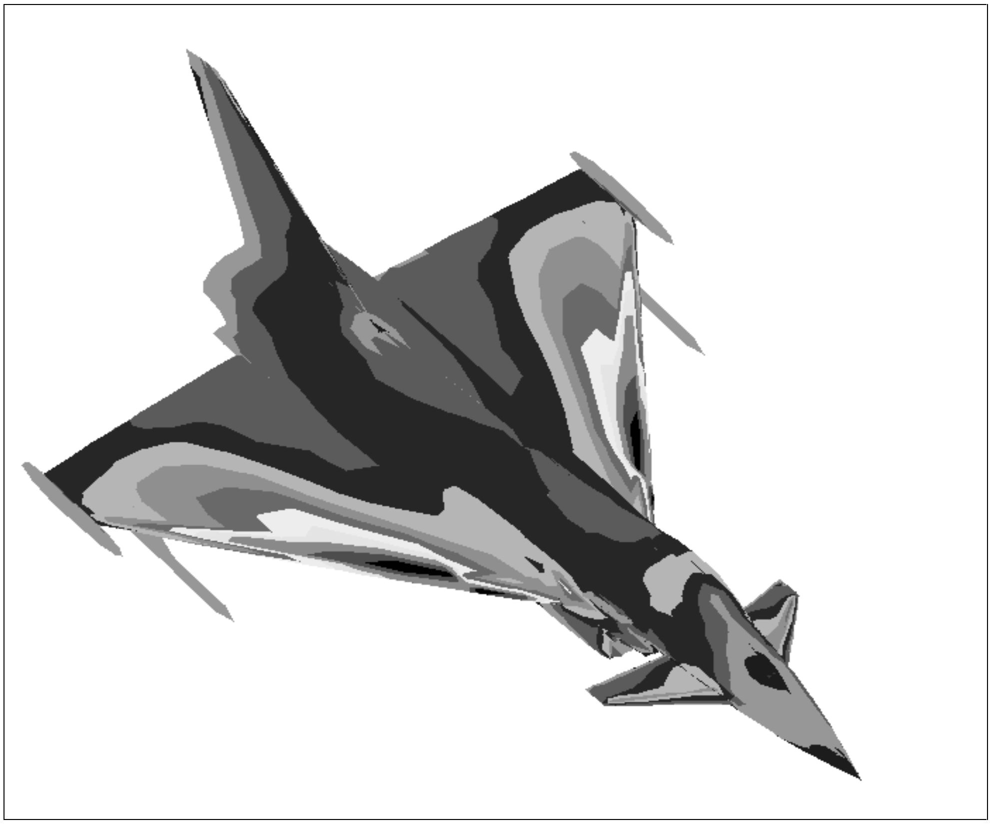


FIGURE 4   FULL AIRCRAFT TEST

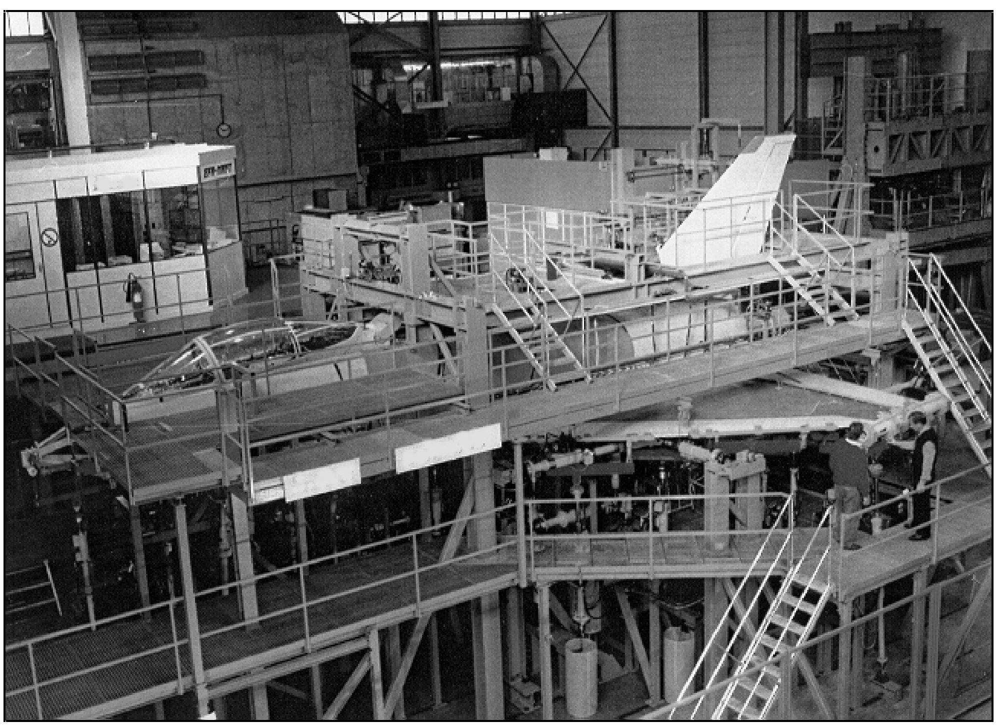
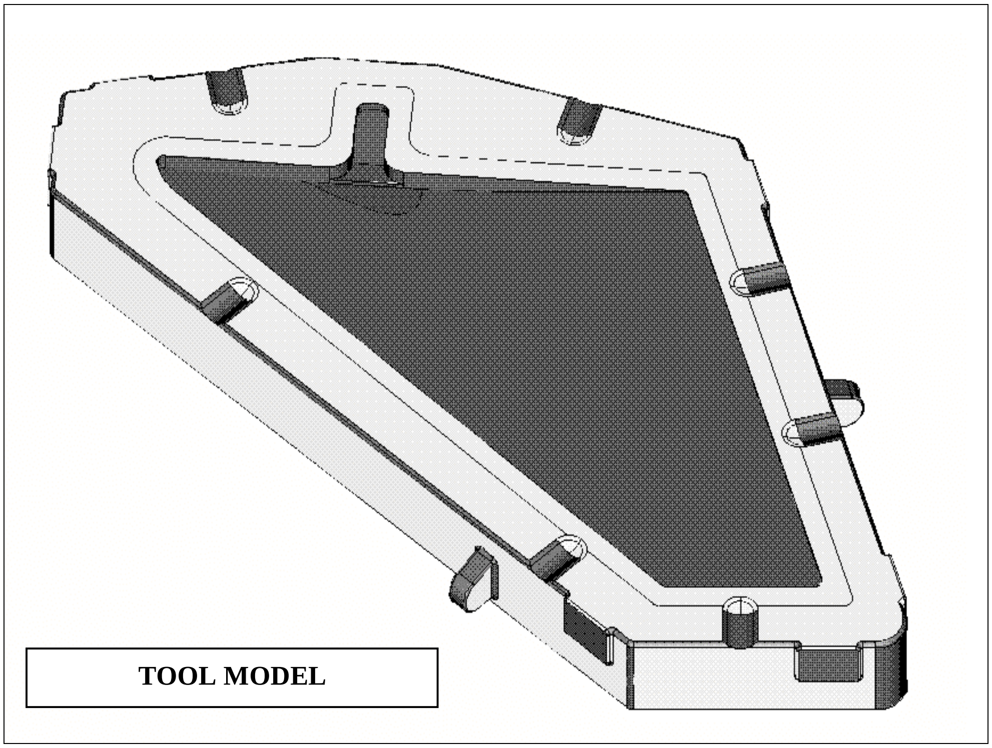
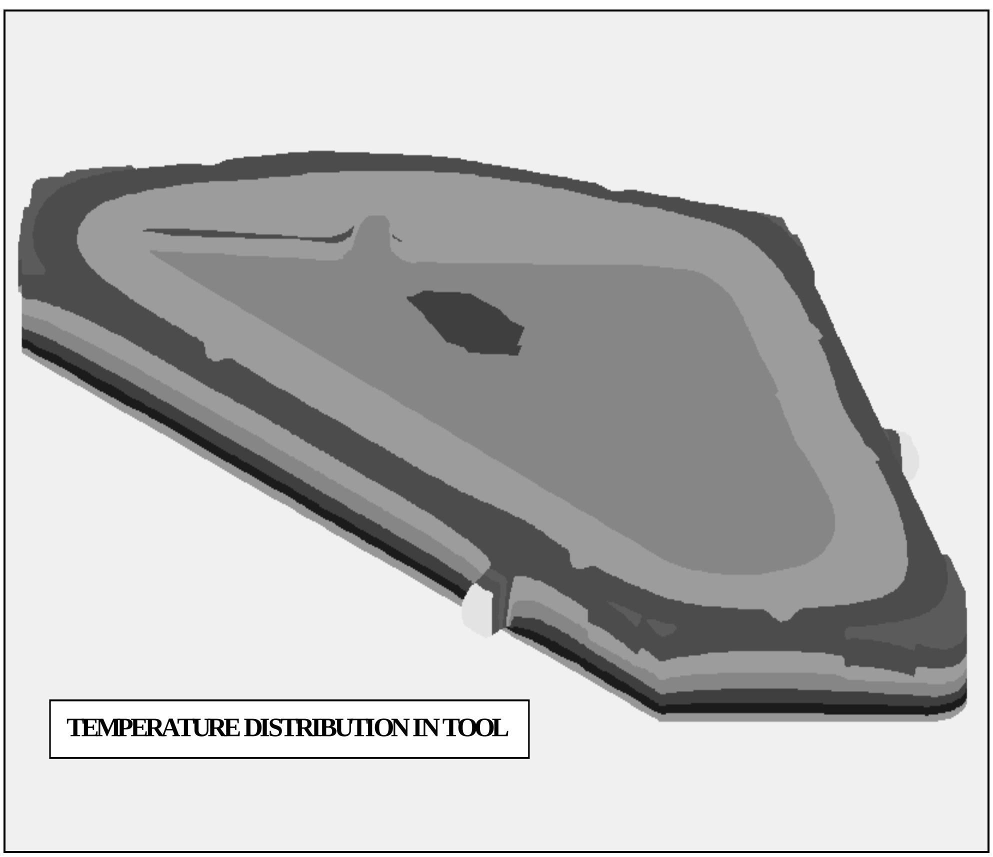


FIGURE 5 THERMAL ANALYSIS OF MANUFACTURING TOOL



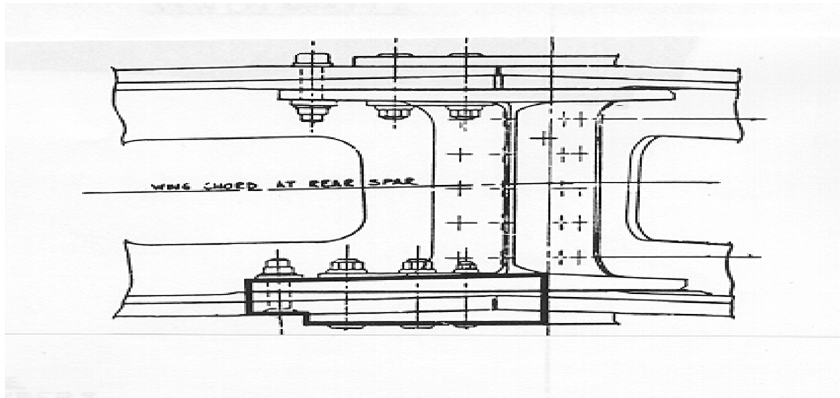
TOOL MODEL



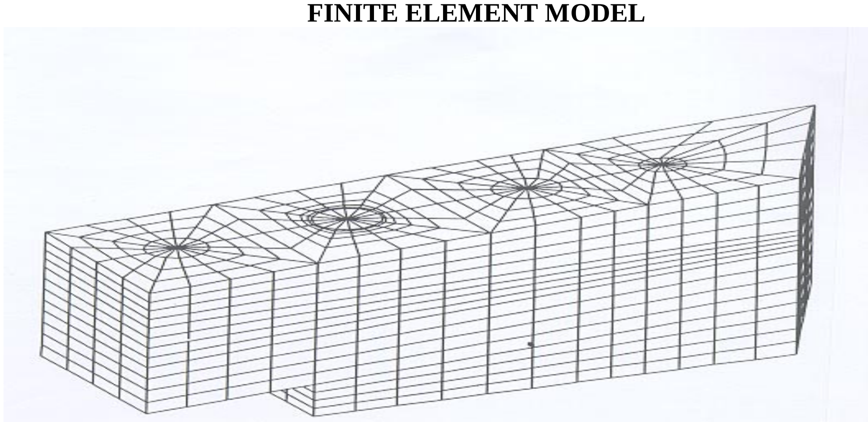
TEMPERATURE DISTRIBUTION IN TOOL

FIGURE 6 TYPICAL DETAIL BOLTED JOINT

BOLTED JOINT DETAIL DRAWING



FINITE ELEMENT MODEL



DEFLECTED STRUCTURE INCLUDING CONTACT AND FRICTION EFFECTS

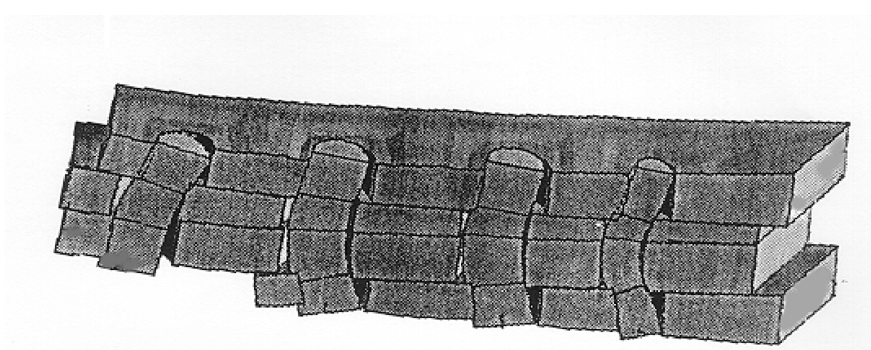


FIGURE 7   FUTURE DEVELOPMENT FOR SIMULATION ANALYSIS