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A DFX TOOL FOR FATIGUE PREDICTION

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ABSTRACT

Fatigue is the most common mechanical failure mode and aside from the economic losses, fatigue is also responsible for failures causing major safety concerns due to its rapid and often undetectable nature before final fracture. Increasingly, the trend in fatigue prevention is towards more sophisticated computational methods integrated with Finite Element Analysis (FEA) nominally implemented at the detailing design stage when sufficient data is available concerning loads, geometry and materials. While industry has accepted highly analytical and experimental techniques, effective and simple design methods for fatigue prevention remains a priority. The concept design phase is where there is most scope for improvement, but places the greatest demands on the designer as little detail exists about the design features. The challenge is to create new DFX tools aimed at the early design phases where there is currently little provision for undertaking fatigue prevention. This paper reports on the development of Concept Design for Fatigue Resistance (CDFR) including: industrial requirements, research methodology, causes of fatigue failure across a number of fatigue failure modes, elements of the fatigue knowledge-base and design metric formulation for prediction of fatigue failure. The technique is verified for welded features only at this stage of development through a number of case studies. A 100% success rate is observed for fatigue failure prediction and approximately 75% success rate in the prediction of the specific fatigue failure mode for the test cases. A high correlation is also observed on the prediction of the failure root causes of each fatigue failure case.

Keywords: DFX, concept design, fatigue, prediction, workbook

1 INTRODUCTION

Fatigue failures are often considered by engineers as the most serious type of fracture because failure can occur when a component is operating under normal working conditions and without excessive overload, and without prior warning [1]. Failure damages reputations causing financial loss and in the most serious cases, loss of life. Studies of the economic effects of fracture in the United States [2] suggest that the total cost of failure in developed countries is of the order of 4% of the Gross National Product (GNP). When this problem is compounded with estimates of up to 90% of failures being caused by fatigue mechanisms, and that improper design decisions may account for around 90% of those fatigue failures [3], then the economic saving through fatigue prevention is great. For over 150 years engineers have known about the fatigue phenomenon from detailed investigations of failures. A great deal of research, both experimental and theoretical, has been conducted and subsequently this has led to a 'toolkit' of fatigue prediction methods e.g. stress-based (infinite life), strain-based (finite life) and damage tolerant fatigue approaches [4].

The 1980s and 1990s saw a rapid increase in computational capabilities, which provided the impetus for the development of Computer Aided Engineering (CAE). CAE software quickly absorbed the many different fatigue models and methods and provided the capacity to conduct simulations of real loads under variable amplitude conditions for small specimens up to full-scale structures. Increasingly the trend in fatigue assessment is towards these more sophisticated computational methods integrated with a Finite Element Method (FEA) [5], initially to supplement component and system testing, but increasingly as a substitute for these activities [6]. Many commercial packages are in existence e.g. MSC.Fatigue, ANSYS Fatigue Module and Fe-Safe. These techniques are nominally implemented at the detailing stage of the design process when sufficient design data is available concerning loads, geometry and material properties. Numerical methods are data intensive and are therefore only applicable at detailing stages of product development and while important to durability analysis these techniques are of limited use at early stages of the design process [7][8]. Current fatigue analysis methods are more effectively used for product durability determination, not for product development [9].

While industry has accepted the highly analytical and experimental techniques, effective and simple design methods for fatigue resistance evaluation remains a priority for industry [10]. Heuristic knowledge and rules of thumb comprise generic fatigue design rules, which can be used in any industrial sector [11]. The approaches aim to either replicate human expertise or facilitate expertise through simple instructions or graphical approaches making decisions about form, suitability and failure. Other more subjective approaches are used in early design phases, e.g. Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Anticipatory Failure Determination (AFD) and Root Cause Analysis (RCA), although the latter is also used in forensic engineering when failures have taken place. Some progress has also been made in developing best practice knowledge and expert systems for fatigue design. The development of a fatigue resistant design knowledge-based system has been explored by McMahon et al [12]. Tumer *et al* [13] developed a taxonomy of failure modes and Leary & Burvill [14] investigated the documentation of case studies in the development of a technique that predicts fatigue limited design. Stone *et al* [15] indicate that similar failure modes occur within products with similar functionality and have a developed a knowledge-based failure analysis tool to enhance failure analysis at the concept design level. At the basic level, ‘lessons learned’ databases are often created by companies to catalogue past failures in an attempt to avoid similar situations when designing variant products. Generally, these methods do not allow quantitative comparisons to be made at early design phases and none have yet to be taken up widely in industry, except perhaps rules of thumb, FMEA and lessons learned databases.

Designing for fatigue resistance still tends to be a highly specialist area conducted by durability and stress analysts in industry and, therefore, fatigue methods are seen as a science rather than practical techniques with which to make sound decisions on. If more fatigue-initiating features were identified earlier, fewer would have to be corrected through analytical methods, testing or simulation, all expensive and time-consuming. New methods must evolve based on consolidated knowledge and lessons learned in order to apply them earlier in the design phase where the cost and time benefits are much greater. Due to the frequency of fatigue failures, many studies have been conducted to describe the modes of failure, identify problem areas and hence improve design for fatigue. This vast collection of knowledge can be tapped to obtain a guide of useful practices that would aid inexperienced designers in avoiding factors that contribute to fatigue failure. This paper presents the research methodology used for the development of a new DFX tool called Concept Design for Fatigue Resistance (CDFR), aimed at the concept and early embodiment design phases where there is little provision for undertaking fatigue prevention currently, and where little detail exists about the designed features.

2 CONCEPT DESIGN FOR FATIGUE RESISTANCE

2.1 DFX Research Methodology

The growing body of DFX tools e.g. Design for Assembly (DFA), Design for Quality (DFQ) etc, have been shown to aid design decision-making processes while overcoming the inherent gap in knowledge at early design phases. The success of these tools is due to quantification of performance metrics, systematic procedure, and comprehensive knowledge in the form of simple workbooks. A research methodology has been developed for the creation of DFX tools [16] and prescribes a series of key stages:

- Requirements Analysis.
- Modelling for Product and Process.
- Selecting Performance Metrics.
- Compiling DFX workbooks.
- Validation.

The structure of the methodology is particularly important when developing design tools, as the quantity of knowledge to be managed is often large and the processes complex. Each stage will be discussed in the context of CDFR development.

2.2 Requirements Analysis

The initial proposal was that CDFR would be applied at the concept evaluation/selection stage of the design process, and function on limited information about each design scheme assessing the alternatives relatively for their fatigue resistance. Ultimately, the concept with the highest fatigue resistance, or lowest failure risk, would be progressed to detailing, which would also be aided. From a survey conducted with industry and focus groups with industrial collaborators [17], it was found that the majority of fatigue assessment occurs during the latter stages of concept development and more commonly in the detailing stage it has been found, the concept phase being limited in its modelling and resources, with the preferred approach being a series of design iterations. It is equally applicable to have CDFR placed during the embodiment/detailing stage, but the use of 'Concept' in CDFR is retained to reflect both modes. The survey also indicated that Computer Aided Designers (CAD) designers would be the main users of CDFR to aid decision-making in the detailing of critical features. Having a feature-based technique (which is the nature of fatigue failures in any case) provides the necessary focus to tackle fatigue problems. Their identification, without the sophistication of a system that 'scans' CAD models, is a difficult and challenging problem, best facilitated through a team-based exercise like FMEA (a technique which already complements quality and reliability analysis at the design stage). A computer-based tool was also favoured by 87% of respondents in the industrial survey. Workbooks are often preferred over computer-based formalisms in the development phase of new DFX tool because they offer an open forum for a team-based analysis [18], help improve understanding of the design problem [19] and have sufficient flexibility to be modified without considerable investment.

At each stage of development CDFR has been linked closely with the requirements of the industrial collaborators and there is therefore great emphasis put on the applicability, usability and positioning of the technique within the Product Development Process (PDP). From the issues raised by industry, it has become possible to devise a capability and utility framework for CDFR. The key requirements of the system have been established as:

- Feature based technique, irrespective of whether on a component or assembly.
- Feature identification is to be aided through some prior process. In this version, designers will be required to conduct an FMEA to identify features with potential fatigue failure mode(s) through the Risk Priority Number (RPN).
- Product Design Specification (PDS) data relevant to the operating conditions of the product should be requested.
- Use of technique to assist detailing for fatigue resistance early in detail design phases.
- The user should be able to clarify the operational details around a feature. If insufficient clarity is provided this could affect confidence and the analysis may be stopped if it falls below a certain threshold value.
- Some fields in the question hierarchy should have user-defined inputs or limits based on expertise in-house or manufacturing capability for example.
- The technique will provide risk measures, post-analysis identifying failure mode occurrence potential with confidence levels.
- Various recommendations and redesign information should be outputted by the technique in order to assist design iteration.
- Favourable as well as unsatisfactory outcomes must be identified, as both are just as important.

2.3 Modelling for Product and Process

The analysis of fatigue failures may involve mechanics, physics, stress analysis, chemistry, material science, manufacturing process knowledge and numerical techniques. Fatigue is therefore a highly complex phenomenon and requires the effective classification and management of the information involved in past failure cases in order to elucidate product and process data. The initial survey conducted asked engineers what they thought were the perceived factors that caused fatigue failures, and together with information from previous research, this aided the generation of a fatigue classification system, called a hierarchy. The collation of 120 fatigue failure cases was essential to the research in order to accumulate sufficient information on the main causes of fatigue failure modes and features as identified through the fatigue hierarchy. These failure cases were collated from a number of texts, journals, expert witnesses, collaborating companies and web sites [20][21].

As avoiding fatigue failure should be a principal goal when designing any mechanism or structure [11], it is necessary to gather cases from a wide range of industries to ensure that the development of CDFR will be representative. The majority of failure cases came from the aerospace sector, 34%, with 22% coming from the automotive sector and 17% from process engineering. The remaining 27% were from the energy, leisure, structural, medical and marine sectors. Approximately 75% of the failure cases were classified as either severe or catastrophic failures resulting in major system damage or total system loss. This is not unexpected due to the hidden danger inherent in many fatigue failures, but it supports the potential economic and safety benefits of any fatigue prevention technique. Each case study was categorised under the classification system and recorded using a computerized fatigue failure database, created in Visual Net with the ability to manage a large number of failure cases with varying failure ontology. The approach allowed the systematic management of the knowledge about each fatigue failure through a database that catalogued fatigue factors under key fields [17]. A standard report on each case study nominally describes:

- The fatigue failure mode type (high-cycle, low-cycle, corrosion, thermal etc).
- The feature type that failed (bolted joint, welded joint, monolithic geometry etc).
- The stage in product development where the cause of fatigue failure was traced back to e.g. design, manufacture, service etc.
- Main causes contributing to each fatigue failure mode type.
- Main causes contributing to fatigue failure for each feature type.

The majority of the features were classified as complex monolithic shapes, with bolted and welded joints being the next two largest categories. CDFR workbook development focuses on welded joint features initially. Due to their complex nature, accurate fatigue life analysis is challenging [22], but they are also of particular interest to industrial collaborators. Figure 1a) shows the relative frequency of fatigue failure modes found in the welded joint case studies. High and low cycle fatigue failure modes dominate with thermal and corrosion fatigue less common. Figure 1b) shows the relative frequency of failure causes found in welded joint case studies; geometry and manufacturing process control/selection being the most common problems. However, 16 root causes spanning all the relevant fatigue failure modes were found just for welded features.

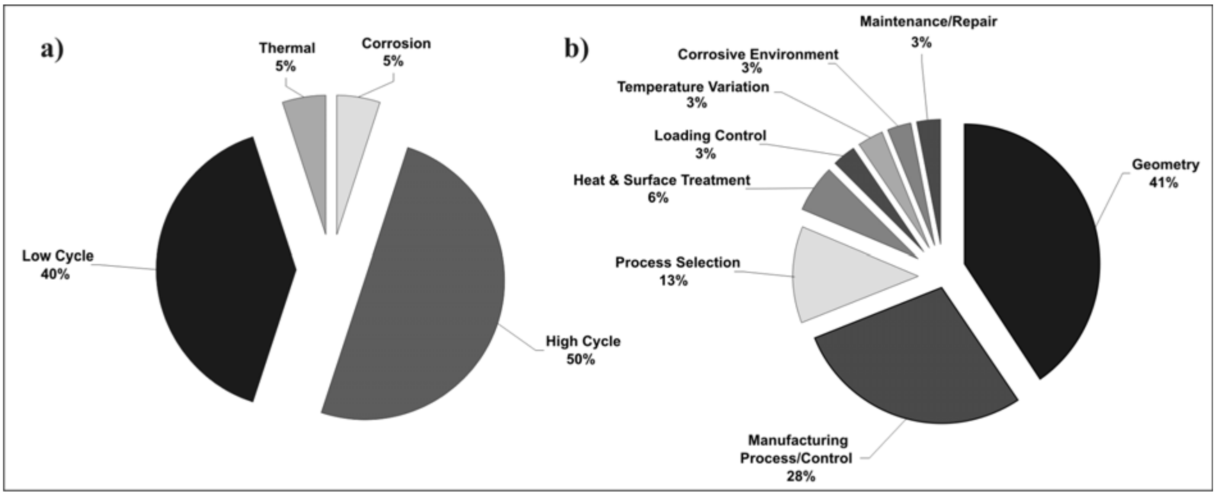


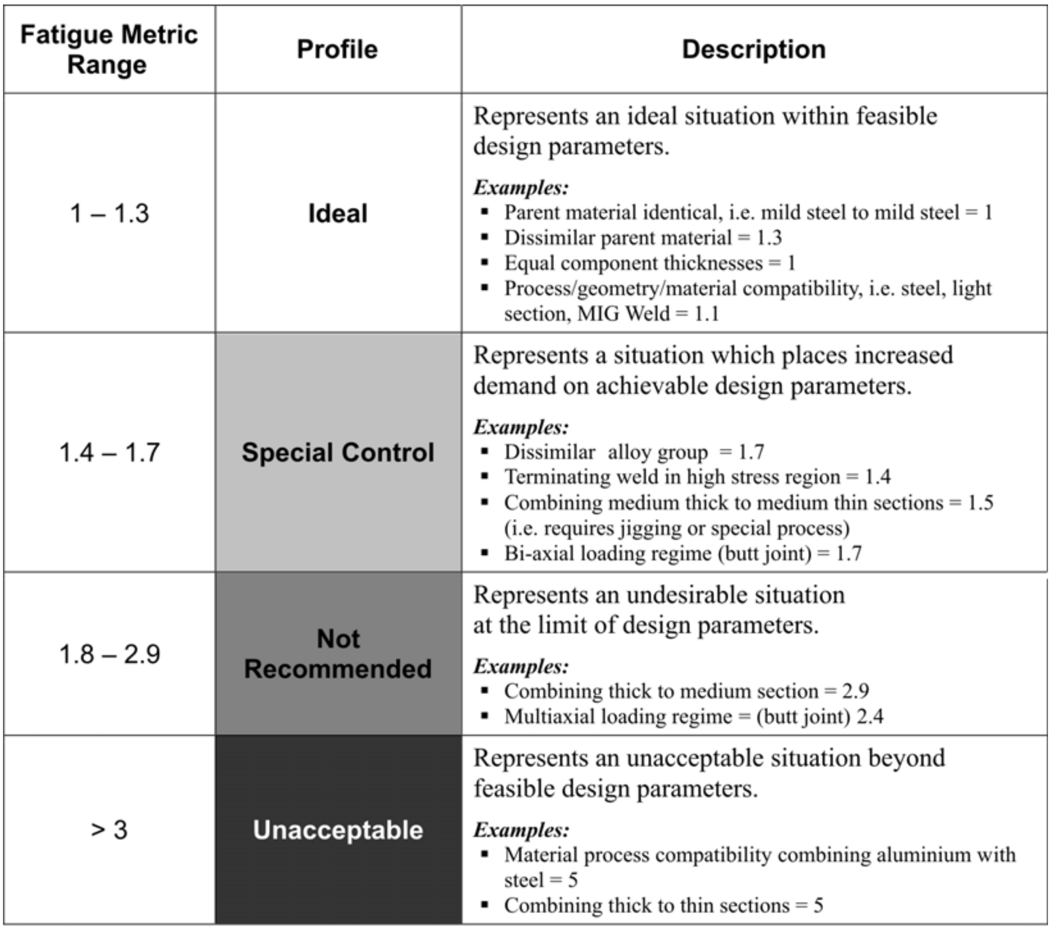
Figure 1. a) Relative frequency of fatigue failure modes found in welded joint case studies b) Relative frequency of failure causes found in welded joint case studies

Ultimately, the CDFR approach uses a hierarchy of design questions evolved from the analysis of the case studies, the classification of causes and was supported by forensic engineering practices. The process flow is organised into five phases:

- Phase 1: Feature identification (define cross-section, joint type, edge preparation).
- Phase 2: Material considerations (parent materials, filler, weldability characteristics).
- Phase 3: Loading regime (principal components, direction, spectrum, mean stress affects).
- Phase 4: Manufacturing processes (material suitability, pre- and post- heat treatment, finishing)
- Phase 5: Service environment (corrosion, maintenance, installation etc).

2.4 Selecting Performance Metrics

An essential element of a successful DFX tool is the performance metrics, also referred to as performance measures or indices [23]. Metrics provide a means of quantifying the performance of a design as a tangible quantity and should reflect the measurable characteristics of interest, in this case, fatigue failure. The development of a performance metric system includes specifying a benchmark that defines the difference between a ‘good’ or ‘poor’ practice. This is done by comparing the performance metric to a standard i.e. does the metric align to best practice design knowledge. The range of engineering disciplines encompassed by the fatigue failure causes makes it impossible to have an absolute metric that is meaningful to each i.e. using a cost metric is common for manufacturing and material in DFX tools, but such a quantity has little relevance when evaluating a geometrical stress raiser or a repeated loading situation. Therefore a relative metric, termed the Fatigue Metric (FM) is used to quantify fatigue design performance under each failure cause. The method of aggregation, range and scale of the FM is also comparable with the more prescriptive DFX tools. The bounds for the FM given in Table 1, and defines the range from “Ideal” (1, unity) to “Unacceptable” (>3), with welding related examples. Other values are interpolated between these limits broadly follow a squared relationship, one which has also been used on previous DFX tool developments [24]. A simple product rule is used to aggregate the FM value. Obviously, 16 ideal values of unity associated with each potential failure cause will return an ideal situation, as far as fatigue is concerned. However, there is a rapid penalisation with individual values greater than 1.3 using the product rule and failure potential will soon be increased, unless good design practice is observed. Both the range and aggregation of the FM help to define clear boundaries of ‘good’ and ‘poor’ fatigue design practice, although it is accepted that apportioning FM values to reflect design knowledge is not an exact science. It is also possible to have ‘modifying’ FM values that are less than unity; these used when a beneficial process is used to reduce the FM penalty e.g. stress relieving or shot peening.



Fatigue Metric Range	Profile	Description
1 – 1.3	**Ideal**	Represents an ideal situation within feasible design parameters. ***Examples:*** ▪ Parent material identical, i.e. mild steel to mild steel = 1 ▪ Dissimilar parent material = 1.3 ▪ Equal component thicknesses = 1 ▪ Process/geometry/material compatibility, i.e. steel, light section, MIG Weld = 1.1
1.4 – 1.7	**Special Control**	Represents a situation which places increased demand on achievable design parameters. ***Examples:*** ▪ Dissimilar alloy group = 1.7 ▪ Terminating weld in high stress region = 1.4 ▪ Combining medium thick to medium thin sections = 1.5 (i.e. requires jigging or special process) ▪ Bi-axial loading regime (butt joint) = 1.7
1.8 – 2.9	**Not Recommended**	Represents an undesirable situation at the limit of design parameters. ***Examples:*** ▪ Combining thick to medium section = 2.9 ▪ Multiaxial loading regime = (butt joint) 2.4
> 3	**Unacceptable**	Represents an unacceptable situation beyond feasible design parameters. ***Examples:*** ▪ Material process compatibility combining aluminium with steel = 5 ▪ Combining thick to thin sections = 5

Table 1. Fatigue metric weightings and example definitions for welded features

In addition to the FM there is also a Response Confidence Metric (RCM) for each FM value. The purpose of the RCM is to ensure that the user has sufficient confidence in the accuracy of their response to the workbook question, which constitutes the FM. The RCM is a relative metric because confidence is a dimensionless quantity and there is no absolute measure suitable. A scale of 0 to 100% is used, divided into three confidence bands high, medium and low. Confidence is more critical for certain key design questions i.e. those associated with loading, material selection, geometry etc, but in terms of potential fatigue failure, the worst case scenario is to have a high FM value combined with a high confidence. An alternative combination is a high FM, low RCM, but this presents more difficulty in predicting a failure mode and therefore it is recommended that sources of low confidence be reviewed immediately. Having developed an understanding and appreciation of the importance of design metrics, it is then possible to consider them as a fundamental element of a CDFR workbook along with fatigue design knowledge representation of good and poor practice in welded joints.

2.5 Compiling DFX Workbooks

The CDFR workbook aggregates FM weightings through an evaluation matrix, with respect to the 16 possible fatigue causes in order to develop a representation of the fatigue failure characteristics of the feature design. The evaluation matrix is shown in part in Figure 2. The complexity of the fatigue phenomenon requires a greater number of metrics than most DFX tools. The development emphasis of CDFR was to maintain simplicity in FM aggregation, some weightings being aligned to more than one fatigue cause, which reflects the relationship between fatigue causes in practice e.g. a thickness ratio is used in geometry, residual stress and heat/surface treatment FM values. Separate sections are required for feature identification and loading because they define fatigue factors related to specific joints i.e. some loading directions and combinations are more damaging to specific joint arrangements than others. FM and RCM values are recorded, when they are relevant, in the blank fields relating to the corresponding workbook question. Only relevant relationships between fatigue factors and questions are left blank while other fields are greyed out in order to reduce possible data input errors. The knowledge supporting the good and poor practice is sourced from a wide range of literature and highlights the knowledge intensive nature of DFX tools [25]. Figure 3 shows a sample of the CDFR workbook content with FM values for four areas: loading proportion, joint edge preparation, section definition and loading spectrum.

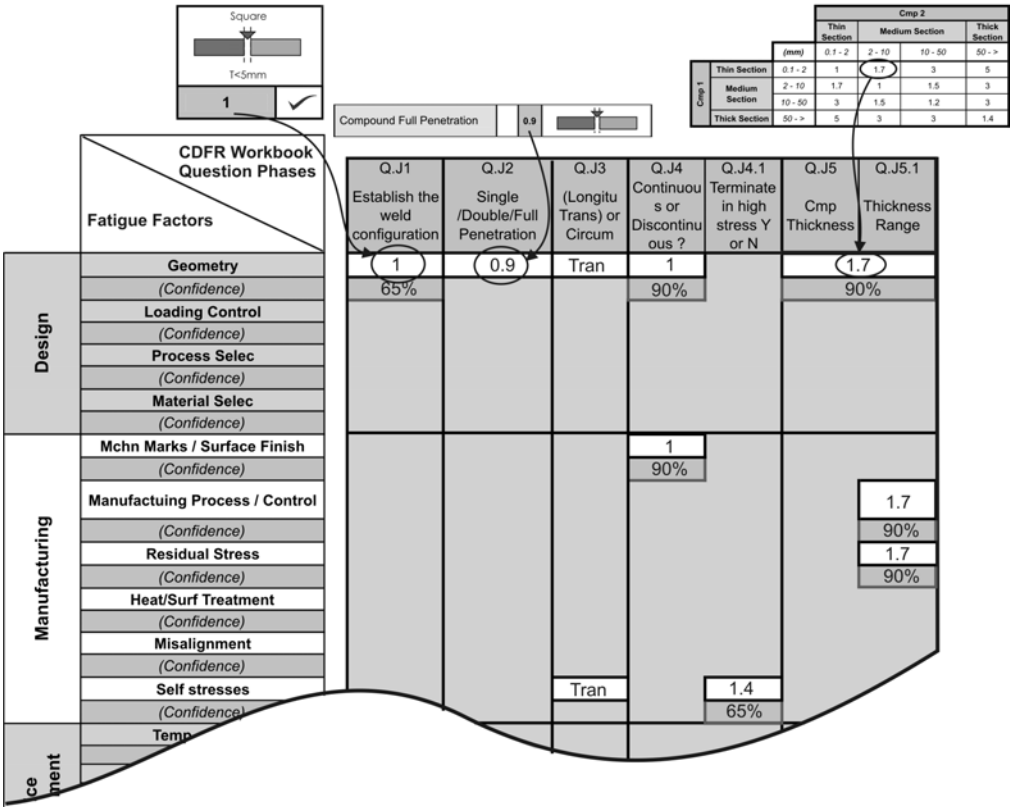
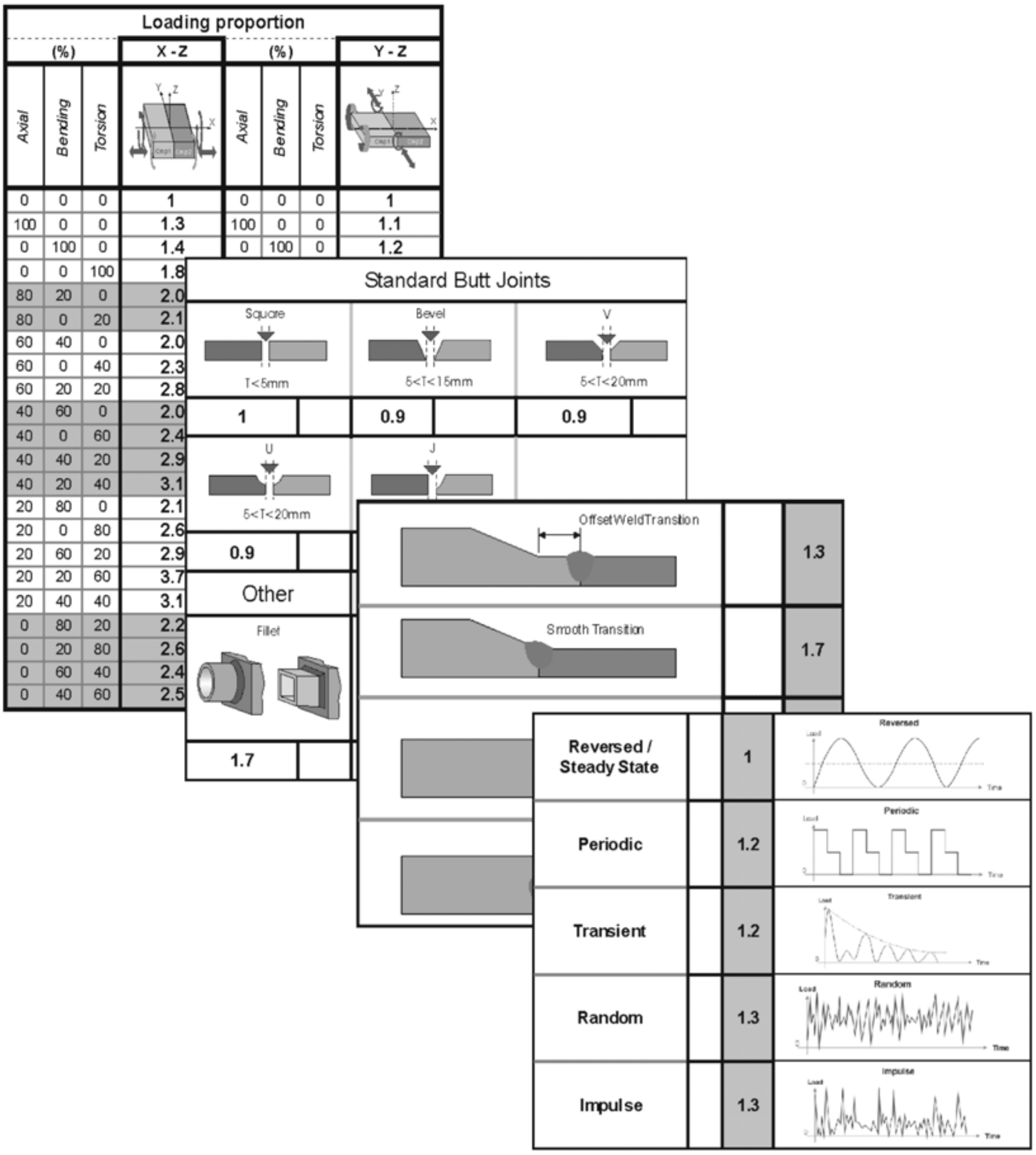


Figure 2. Fatigue metric evaluation matrix

The main function of the matrix is to allow FM values to be aggregated for the design case in question; the highest values of FM for each factor being the potential causes of fatigue and overall, an indicator of fatigue failure for the designed feature. A separate approach is needed for the prediction of a specific fatigue failure mode (high-cycle, low-cycle, corrosion fatigue etc). This is based on correlating the frequency of failure causes to the failure mode type for past failures, and then mapping these failure mode profiles across to the FM values obtained in the matrix. This allows for multiple failure modes to be considered at once, but is heavily reliant on the number of past failure cases in the database as some common and important failure causes may not be evident if sufficient numbers have not been recorded.



Loading proportion							
(%)			X - Z	(%)			Y - Z
Axial	Bending	Torsion		Axial	Bending	Torsion	
0	0	0	1	0	0	0	1
100	0	0	1.3	100	0	0	1.1
0	100	0	1.4	0	100	0	1.2
0	0	100	1.8				
80	20	0	2.0				
80	0	20	2.1				
60	40	0	2.0				
60	0	40	2.3				
60	20	20	2.8				
40	60	0	2.0				
40	0	60	2.4				
40	40	20	2.9				
40	20	40	3.1				
20	80	0	2.1				
20	0	80	2.6				
20	60	20	2.9				
20	20	60	3.7				
20	40	40	3.1				
0	80	20	2.2				
0	20	80	2.6				
0	60	40	2.4				
0	40	60	2.5				

Standard Butt Joints					
Square T<5mm		Bevel 5<T<15mm		V 5<T<20mm	
1		0.9		0.9	
U 5<T<20mm		J			
0.9					

Other	
Fillet	
1.7	

OffsetWeldTransition		1.3
Smooth Transition		1.7

Reversed / Steady State		1	Reversed
Periodic		1.2	Periodic
Transient		1.2	Transient
Random		1.3	Random
Impulse		1.3	Impulse

Figure 3. A sample of the CDFR workbook knowledge with fatigue metric values

2.6 Verification

The verification stage was conducted using 18 failure cases and supported by one field improvement case study from an industrial collaborator. This phase of research tests the performance of the technique in predicting fatigue failure, its mode and causes, but also the usability and applicability of CDFR in an industrial context. The majority of the cases (90%) used were also part of the initial study to evaluate failure modes and priority causes. Although it seems that the exercise should be a ‘selffulfilling prophecy', it is important that the known fatigue failures, modes and causes are correctly identified to have confidence in the next new feature analysis. The sample covered a range of industrial sectors, which reflects the versatile nature of welding fabrication. Verifying the accuracy of the CDFR tool is determined by evaluating three analysis outputs:

- Fatigue failure prediction: Does CDFR predict fatigue failure, regardless of mode or mechanism?
- Fatigue failure mode prediction: Does CDFR predict the specific fatigue failure mode (high cycle, thermal, corrosion fatigue etc)?
- Fatigue cause prediction: Does CDFR predict, through the 16 fatigue causes, the dominant root causes of the fatigue failure mode i.e. loading control, geometry, material selection, etc?

The results for one particular verification case is shown in Figure 4, and relates to the catastrophic low-cycle fatigue failure of a three-wheel motorcycle frame caused by bending fatigue [26]. Cracks propagated from several weld locations with the dominant position being located at the junction between the original motorcycle frame and the cargo box frame as shown in the schematic. The frame replaced the original rear wheel of the motorcycle in order to allow a cargo box to be incorporated. Dynamic cyclic loading experienced by the motorcycle in service coupled with poor detail design of the welded joints caused the stresses to exceed the material fatigue limit. The pivot point is constructed from a 'swing arm stud' plate lapped by the upper and lower tubes of the frame, all made from low carbon steel. The Pareto chart output combines both the FM and RCM after answering the workbook questions, as shown in Figure 4, CDFR Fatigue Failure Results section, and shows that loading control and geometry are dominant failure causes for this case study (both being above 3 and therefore unacceptable), which matches the forensic engineering assessment of the case failure report.

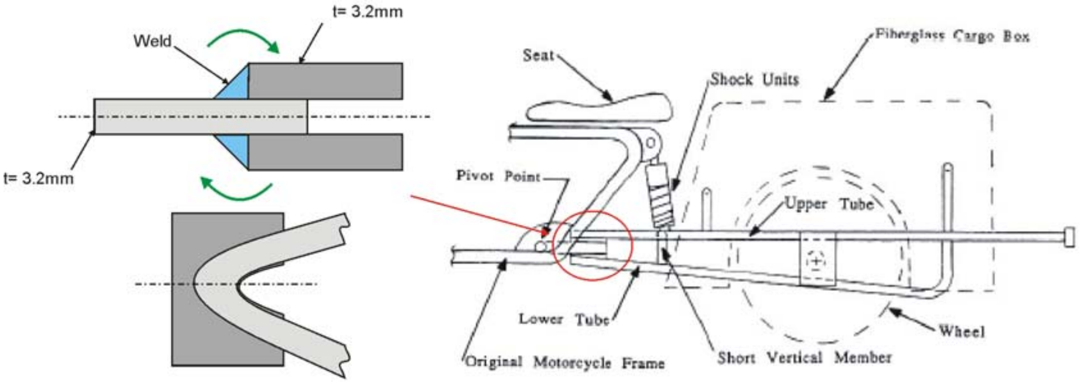
Analysing all 19 case studies and calculating FM values produces a dilemma. What is the simplest way to create a benchmark value of FM which relates to fatigue failure? Figure 5 shows two possible approaches: one using the maximum FM value obtained, and the other, an average FM value over the 16 possible causes of failure. The latter produces a fatigue failure level less than that set for an unacceptable situation (<3) i.e. possible survival. This low level is caused by fatigue factors such as inspection interval and material flaws, which have little or no influence on welded joints and therefore have a corresponding 'Ideal' FM of 1, lessening the impact of higher FM values. Conversely, all verification cases have at least one FM value that exceeds 3, with 9 being a mean FM maximum value across the 19 case studies. In order that fatigue failure is predicted satisfactorily in new design features therefore, a maximum FM value greater than 3 in isolation would be considered a priority cause of failure leading to possible fatigue failure.

Details of the specific fatigue failure mode predictions for each of the 18 failed case studies and correlations of the fatigue failure causes are not described here, but the results are shown in Figure 6, and may be compared to the original case study analyses in Figure 1. In summary, for the case studies used in verification, CDFR has:

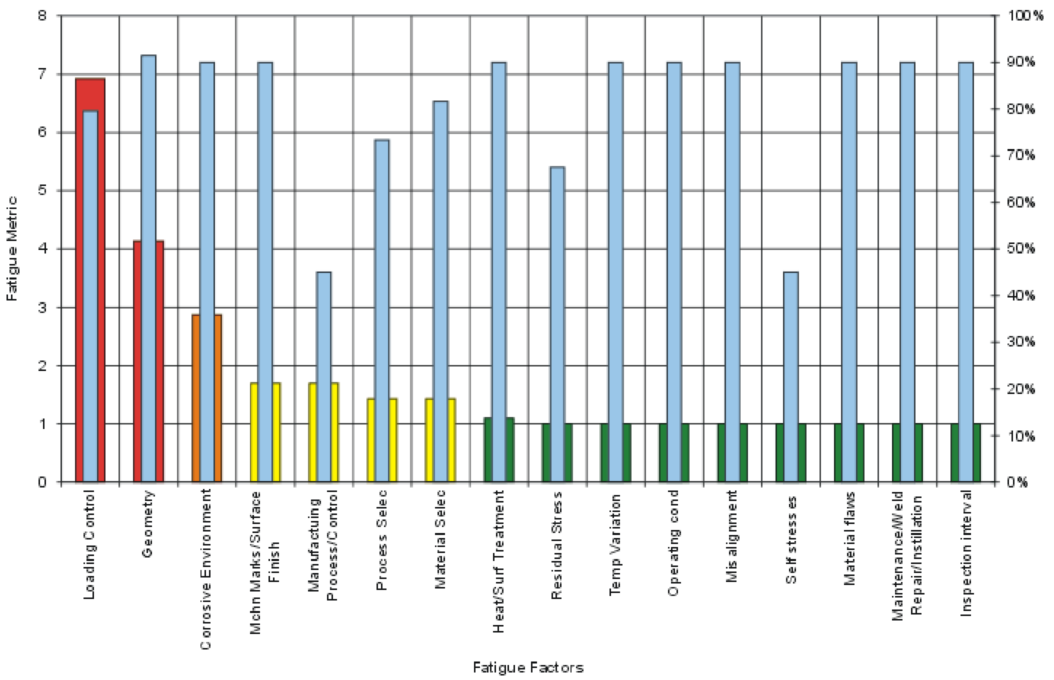
- Predicted fatigue failure for 100%.
- Predicted the specific fatigue failure mode for 75%.
- Predicted the root causes of failure for 80%.

The first two verification percentages given above are based directly on successfully predicting fatigue failure and the mode of fatigue compared to the case study details. The last issue concerns the accuracy of failure cause prediction, which is complicated by the fact that the failure causes are usually expert judgment and never precisely known, and in several cases, more than one root cause has been identified as contributing to final fatigue failure, and not necessarily having equal contribution. The simple percentage measure of root cause prediction accuracy used here suggests that for all identified root causes, whether one, two or more, CDFR predicted 80% of the total for all case studies. More complex assessments of the accuracy in prediction at this stage of tool development would be subjective and misleading with the limited number of case studies used in verification.

CASE STUDY DETAILS	
Case Title and Reference	Three Wheeled Motorcycle Frame [26]
Description	Failure of the frame caused through bending fatigue at several locations near the welds in low carbon steel. The bending stresses experienced by the frame in service were enhanced through poor detail design contributing to failure.
Manufacturing Process	Tungsten Inert Gas Welding
Principal Loading Plane	Bending
Material	Low Carbon Steel
Fatigue Failure Mode	Low Cycle Fatigue
Failure Root Cause(s)	Geometry, Loading Control



CDFR FATIGUE FAILURE RESULTS



Predicted failure mode	Low Cycle Fatigue
Maximum FM	6.9

Fatigue Factor(s)	FM	Fatigue Factor(s)	FM
Loading Control	6.9	Manufacturing Process/Control	1.7
Geometry	4.1	Process Selection	1.4
Corrosive Environment	2.9	Material Selection	1.4
Machine Marks/Surface Finish	1.7		

Figure 4. Case study details and CDFR results

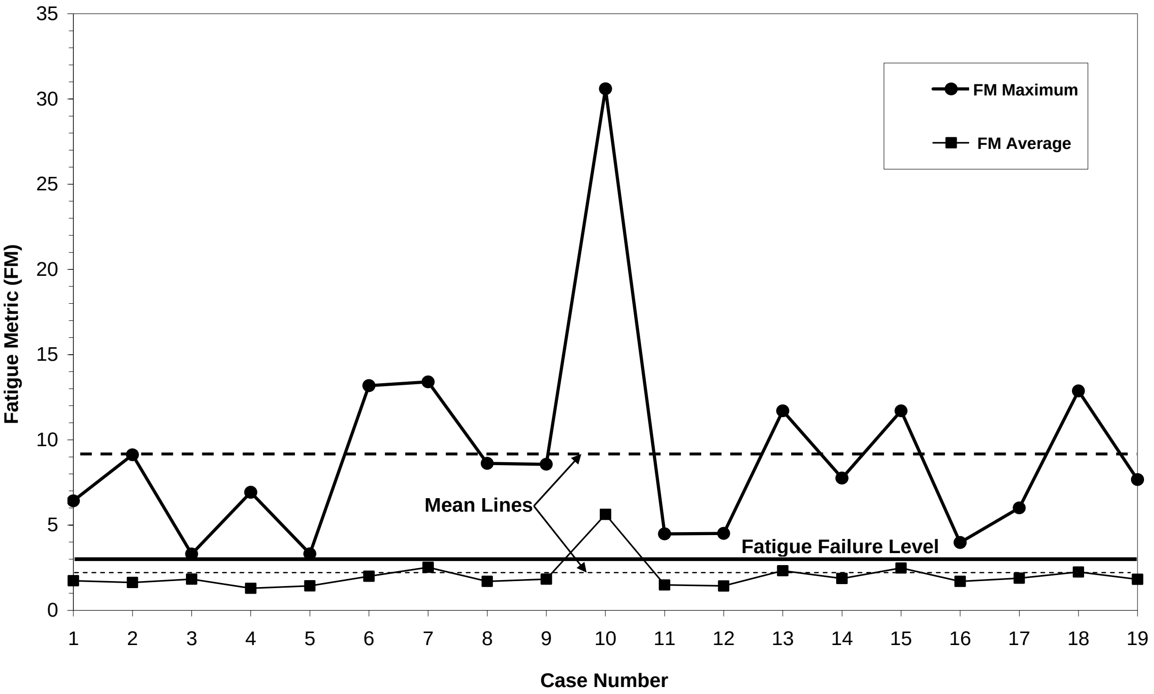


Figure 5. Average and maximum fatigue metric results for 19 welded joint case studies

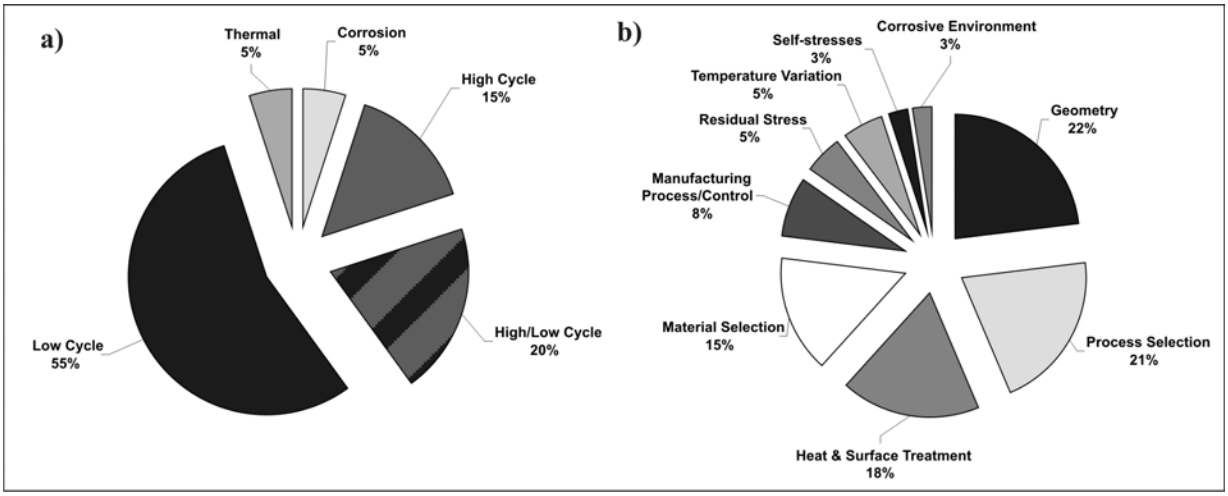


Figure 6. a) Relative frequency of fatigue failure modes predicted for welded joint case studies
b) Relative frequency of failure causes predicted for welded joint case studies

3 CONCLUSIONS

A current trend is towards the use of computational approaches for fatigue and durability simulation. These approaches are heavily reliant upon having detailed information describing the geometry, material properties, loads associated with design features in order to conduct a complete analysis. Subsequently, fatigue assessment usually appears late in the design process where design, manufacture and service data matures. Experience shows that although computational tools are of great value in designing for fatigue resistance, basic design errors still occur resulting in costly failures impacting on business performance in terms of increased cost through redesigns, warranty, product liability and also in terms of customer safety and loss of loyalty. Industry competitiveness is increasingly determined by the capacity to achieve ‘right first time’ designs making early design decisions critical in preventing lengthy design iterations and costs. DFX tools are proven methods aid decision making at early design stages where redesign costs are lower with benefits in relation to many competitiveness measures [27]. The application of CDFR in an integrated product development process may enhance decision making in the important area of failure determination, something that current analytical fatigue design processes do not provide. It is not the intention to replace the more computational fatigue methods, as they unquestionably have their place in fatigue life prediction, but to provide the justification for designers to redesign potential problem features at or just after concept development, where the costs of redesign are lower. Redesigns have then to be balanced against other design considerations such as product cost and manufacturing feasibility, which may be measured by other DFX techniques.

This paper has examined the early developments and validation of a new DFX tool for fatigue resistant designing in a workbook format. Through a rigorous research methodology, failure case study analysis, fatigue knowledge collation and structuring, and the development of new fatigue design metrics, it is possible with confidence to predict fatigue failures at early stages of the design process, with minimal information processing. The prediction of specific fatigue failure modes and root causes is also possible with high degree of confidence. A range of application modes have emerged that can add value to the approach at different stages of the design cycle, and include: prediction of fatigue failure, fatigue failure mode and fatigue causes; assist in concept selection; as a design practice advisor to assist detailing for fatigue resistance, and as a reactive, failure analysis aid. Feedback from industrial collaborators suggests a number of benefits may be realised through CDFR's effective and integrated use in product development:

- Provides a 'safety-net' to help eliminate the most significant fatigue-initiating features from the design earlier helping to reduce associated failure costs in the design process.
- As an educational tool for inexperienced designers and engineers.
- To encourage stress analysts and designers to open up communication earlier.
- Provides a mechanistic way of capturing the knowledge related to new failure cases in fatigue useful for the development of a company-specific database or to enhance RCA and FMEA.
- Opportunities for reduction in manufacturing and service failure costs and reduction in lead times to improve competitiveness through designers producing more durable designs earlier.

Future work will entail expanding the number of features that CDFR can effectively process, particularly bolted joints and monolithic features, using the methodology demonstrated and proven for welded features. In fact, knowledge of all types of mechanical failure could also be examined so as not to lose vital information useful in avoiding other types of failure and the CDFR framework could provide a methodology for the development of like techniques for other failure modes such as wear or brittle fracture. Eventually the intention is to integrate three powerful and proven approaches: Expert System (ES), Knowledge Based System (KBS) and Case-Based Reasoning (CBR), in order to implement CDFR in a computer-based system and therefore improve speed, accessibility, acceptance and design re-use capabilities [17]. The increasing prominence of CAE tools in engineering practices has also resulted in a long-term development objective being the adaptation and integration of the fatigue knowledge embedded in CDFR for use in a CAD modelling systems to facilitate direct 'scanning' of a solid model to identify fatigue initiating features rapidly. This would require interfacing the proven processes and knowledge developed directly with a commercial CAD package, a facility that some CAD packages already posses, but has yet to be widely exploited as a tool such as Unigraphics, NX Check-Mate/NX Quick Check®.

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