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THE USE OF RETROSPECTIVE FAILURE CASE STUDIES IN THE DEVELOPMENT OF A FATIGUE PREVENTION TECHNIQUE

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1 Introduction

The fatigue research community has carried out extensive work investigating the nature of fatigue failure using analytical, semi-empirical and experimental methods, which has led to a 'toolkit' of techniques to evaluate the fatigue life of components. Designing for fatigue resistance tends to be a highly specialist area conducted by durability and stress analysts and is often considered as a science rather than a practical tool. This paper presents the results of a study of 120 retrospective fatigue failure cases used to aid in the development of a new technique called Concept Design for Fatigue Resistance (CDFR), that assists detailing for fatigue resistance early in detail design phases. The more fatigue-initiating features identified earlier in development, the fewer that have to be corrected through finite element analysis (FEA) models or found using intermediate prototypes, both expensive and time-consuming to develop.

2 Background

When a component or product is repeatedly subjected to loads of sufficient magnitude, a fatigue crack will eventually propagate in some highly stressed region, normally at the surface, until final fracture occurs [1]. It is important to realise that even "perfect" components have a finite life and will eventually fail after a certain period through fatigue mechanisms. Fatigue failures are the most common mode of mechanical failure with estimates of 60 to 90% not untypical [2, 3]. In fact, Osgood stated that, "…*all machine and structural designs are problems in fatigue*" [4]. The cost of fatigue failure to industry and the customer cannot be judged accurately, but losses due to fracture mechanisms annually are over $100Billion in the US [3]. Aside from the economic losses, fatigue is also responsible for failures causing major safety concerns due to the rapid and often undetectable nature of the final fracture. Improper design decisions account for the majority of all fatigue failures and the need for effective design methods for fatigue resistance evaluation remains a priority for industry [2, 5].

The history of fatigue design dates back to the middle of the nineteenth century, marked by the industrial revolution [6]. Extensive work has been carried out by the fatigue research community investigating the nature of fatigue failure using analytical, semi-empirical and experimental methods [7, 8]. This has led to a 'toolkit' of techniques in order to evaluate the fatigue life of components under varying load conditions and under numerous design objectives, such as: long life, low weight, high strength, high reliability or perhaps all four simultaneously. Designing for fatigue resistance therefore tends to be a highly specialist area conducted by durability and stress analysts. Increasingly the trend in fatigue design is more towards Finite Element Analysis (FEA) integrated with the fatigue techniques developed, it is suggested, to increase utility and acceptance by designers. FEA fails to enumerate fatigue problems to the designer early in the design process, the earliest feasible stage being just after the concept design phase, and are much better aligned to the later stages of detailing when data associated with geometry, material properties and service loads matures. It is the early stages of the design process that presents the greatest demands on the designer and where there is most scope for reduction of fatigue-initiating features. It is also the area that presents the greatest challenge in the research and development of a new technique to assist the process of designing for fatigue resistance, and currently there is little provision for undertaking fatigue prevention here. Essentially, the more fatigue-initiating features identified earlier, the fewer that have to be corrected through FEA models or found using intermediate prototypes, both expensive and time-consuming to develop. A designer would want to know as soon as possible whether their design would develop a fatigue problem, and if so, how to resolve it.

This paper presents the results of a study of 120 retrospective fatigue failure cases that will ultimately aid the development of a new design for fatigue resistance technique called Concept Design for Fatigue Resistance (CDFR). The storage, profiling under key fields and knowledge classification of the fatigue failure cases was aided by a bespoke database system. The failure cases collated elucidate key issues such as failure mode, feature type and contributing factors to fatigue failure modes qualifying the development of the technique. The perceived benefits by industry are to enhance durability appraisal of designs in order to reduce fatigue-initiating features and associated failure costs earlier in the design process than is typically feasible. The aim is so that the design can be as near faultless as possible with a high confidence, so that time, effort and costs can be reduced in later development stages. The ultimate goal is to produce a technique that is accessible by designers further augmenting the Design for 'X' portfolio of techniques, which includes Design for Assembly (DFA), Design for Manufacture (DFM) and Design for Quality (DFQ).

3 CDFR development issues

Prior to the development of CDFR, a detailed study was undertaken concerning current industrial practice in designing for fatigue resistance, the *prior art* and attitudes towards the proposed technique [5]. The results are summarised in Figure 1. The survey revealed that there is a demand within industry for a new technique that provides early indications of potential fatigue failure issues and elucidates the solution with redesign advice where possible. Future priorities identified in a recent survey for the pressure equipment industry [9] also highlighted the need for more simplified methods in the assessment of fatigue resistance. However, the trend as previously stated is towards more sophisticated computational models using FEA. A number of systems may be applied in order to provide information useful to designers at the early stages of the design process in order to avoid failure problems generally. At the very 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. Taking this idea a stage further, research into a taxonomy of failure modes is also being investigated [10, 11]. Some progress has been made in developing best practice guidelines and Expert Systems (ES) for fatigue design [12] and research in the development of a fatigue resistant design Knowledge-Based System (KBS) has also been conducted [13].

Other investigators are looking into documenting case studies in the development of a technique that predicts optimum product development paths for fatigue limited design [14]. By incorporating many of the ideas discussed in the proposed CDFR technique and concentrating on one specific area, that concerning fatigue, the knowledge needed is reduced [15] and its effectiveness will be improved. Conversely, it has been suggested that knowledge of all types of mechanical failure should be examined in any methodology proposed for an assessment of fatigue resistance so as not to lose vital information useful in avoiding other types of failure [16].

Industrial Fatigue Design Practice

- Failure mode identification not rigorous.
- Intuitively, the designer knows what is bad! Don't perform analyses though, just detail.
- Designer must try and filter out problems before passing on to stress analyst.
- Occasionally designers call in stress analysts to ask about a feature. Some are not proactive enough to solve the problem in this manner.
- Analysis and testing is required to qualify new features. May stifle innovation.
- FEA not realistic because still get failures in field. Must be supported by experience.
- Have had these types of techniques before e.g. DFA. Did not reach the right audience, and not used a great deal now. They are not seen as a priority. Change in mind-set needed.
- A 'lessons learned' database exists somewhere, but mistakes are still being made.
- Suppliers give CAD models – no idea of fatigue or durability. Can this method provide some assistance here?

Proposed CDFR Approach

→ Design for fatigue guidelines would be useful, provided in a simple manner.

→ Influence designer using rules and make it a good design from the start.

→ Design technique runs a checklist comparing design to the knowledge.

→ Need something useful to the company, not just general.

→ Cannot be subjective like DFA.

→ Platform more suitable as a printed document, but can write as software.

→ An expert system? Gives options on what to do. Give the user the choice.

→ 'Lessons learned' database would be beneficial.

→ Useful to capture and disseminate this knowledge.

→ Keep as simple as possible!

→ Must have correlation to practical results.

→ Help to define detail, not select best concept.

→ New and experienced designers alike to benefit from new technique.

Figure 1. Industrial comments on current fatigue design practice and proposed CDFR approach

The initial proposal for the structure CDFR was to have a technique that would be applied at the concept evaluation/selection stage of the design process, and functioned 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 will also be aided. In reality, the concept phase of industrial product development processes is limited in its formalisation and resources, with the preferred approach being a series of design iterations [5]. It is equally applicable to have CDFR placed during the embodiment/detailing stage and the use of 'concept' in CDFR is retained to reflect both application modes. Previous work suggested that 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 Failure Mode and Effects Analysis (FMEA). A computer-based tool is also favoured (87% of respondents surveyed [5]) but equally the method could be paper-based once the knowledge needed to assess a variety of fatigue features has been developed. It should be noted that a paper-based analysis is especially advantageous for team-building [17] and has in the past, also deepened the understanding of the problem in hand, e.g. DFA [18].

Returning to the identification of features, one component may have tens of features that are potential fatigue initiators, especially at early design phases. FMEA is useful in this context. The criticality of a component or feature can be assessed using FMEA with between 70 to 80% of potential failure modes also identified at the design stage [19]. It also provides the user with risk priority measures, which are the product of likely occurrence, severity and detectability for design features, components or whole systems. FMEA can however be highly subjective relying on the quality of information captured from previous product failures and the experience of the design team performing it. The proportion of companies in the UK conducting FMEAs is about 60% [20], and current trends in risk management suggest an increase in the future. It would therefore be advantageous to integrate FMEA practices with CDFR for industrial implementation purposes due to its popularity, effectiveness and alignment with the early stages of the design process. In order to augment the fatigue design process the level of subjectivity associated with FMEA will however be reduced through the provision of knowledge on particular fatigue failure modes and their causes.

4 Analysis and results of retrospective fatigue failures

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 any attempt to provide a non-analytical or non-empirical assessment of potential fatigue problems requires the effective classification and management of the data involved in these past failure cases. The initial survey conducted asked the engineers what they thought were the perceived factors that caused fatigue failures [5], and together with information from [15], this aided the generation of a fatigue classification system. The approach allowed the systematic management of the knowledge about each fatigue failure through a database that catalogued fatigue factors under key fields. The classification system is shown in Figure 2. In order to prescribe the source of the failure mode, it is necessary to look more closely at subdivisions of the primary factors. The secondary fatigue factors define the areas where incorrect decisions are made within design, manufacturing, service environment, post-production and abuse.

The research initially uses information relating to 120 fatigue failures collated from a number of key references, expert witnesses, collaborating companies and web sites [21-24]. As avoiding fatigue failure should be a principal goal when designing any mechanism or structure, 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 automotive (22%), process engineering (17%) and the remaining 27% 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 [25]. 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. The level of detail provided in failure reports, journal papers and texts for each case varied widely, with a core of 50 cases having a large amount of detail and 70 secondary cases. The limited amount of detail for several cases made it difficult to define particular failure factors, which may be subjective anyway e.g. abuse or maintenance.

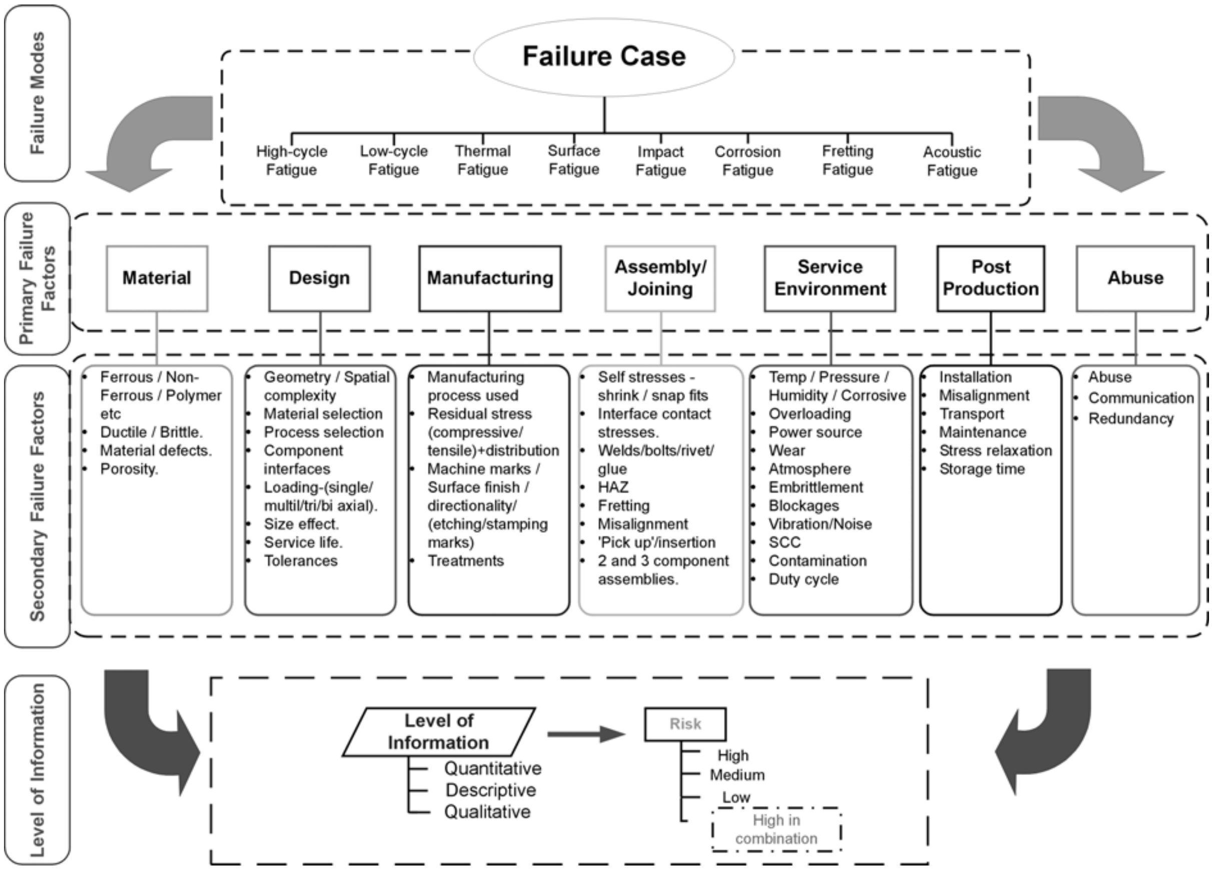

Figure 2. Classification system for fatigue failure case data

Each case study was categorised under the classification system discussed and recorded using a computerised database system. A standard report on each case study nominally describes:

- The fatigue failure mode type (high-cycle, corrosion, fretting etc).
- The feature type that failed (bolted joint, weld, complex 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 factors contributing to each fatigue failure mode type.
- Main factors contributing to fatigue failure for each feature type.

The failure modes and the primary fatigue factors are well established and can be defined clearly through current engineering knowledge. However the secondary fatigue factor tier describes in greater detail the root cause of the failure or contributing factor. This section has the flexibility to incorporate new factors if they have not been explored in the analysis of the cases collated thus far. Figure 3 shows the relative frequency of the features where the fatigue failure initiated within the 120 cases collated. Note that the features pictured are general in nature, but all will have specific stress raisers which are not shown e.g. monolithic types typically have other features such as a holes or slots. Over a third of the features were classified as complex monolithic shapes, but also bolted and welded joints figured highly. High-cycle (42%) and low-cycle (31%) emerged from the sample as the most common fatigue failure modes, as shown in Figure 4. Scientific and engineering knowledge describing these failure modes is well established and therefore engineers are more aware of their characteristics compared to say fretting or acoustic fatigue (none were actually sourced for the latter). It is also possible that a number of failure modes in combination may have caused failure of the individual case considered i.e. low-cycle fatigue with corrosion. These mechanisms are known to be fatigue accelerating when coupled with the either high- or low-cycle characteristics.

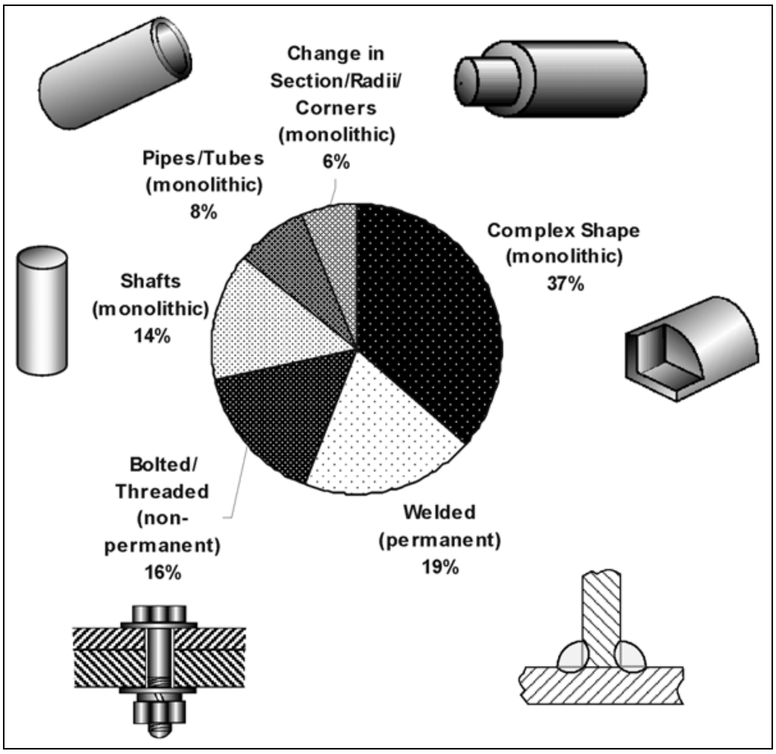

Figure 3. Feature types found in fatigue failure cases

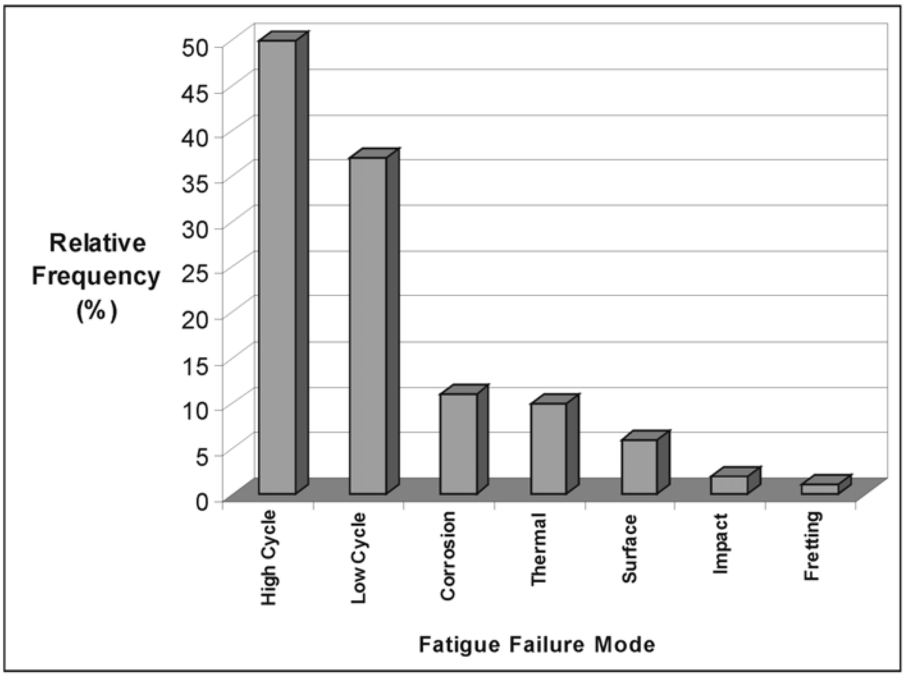

Figure 4. Fatigue failure modes found in failure cases

Most failures are attributable to poor decisions made during design (33%) and manufacturing (28%), as shown in Figure 5. Design is the stage at which the most fundamental decisions are made and this supports previous research [5]. Manufacturing imparts many additional stresses and stress raisers on components which are given little attention in fatigue design typically. The remaining factors of service-environment, post-production, assembly and joining and other issues account for 42% of the failures in total.

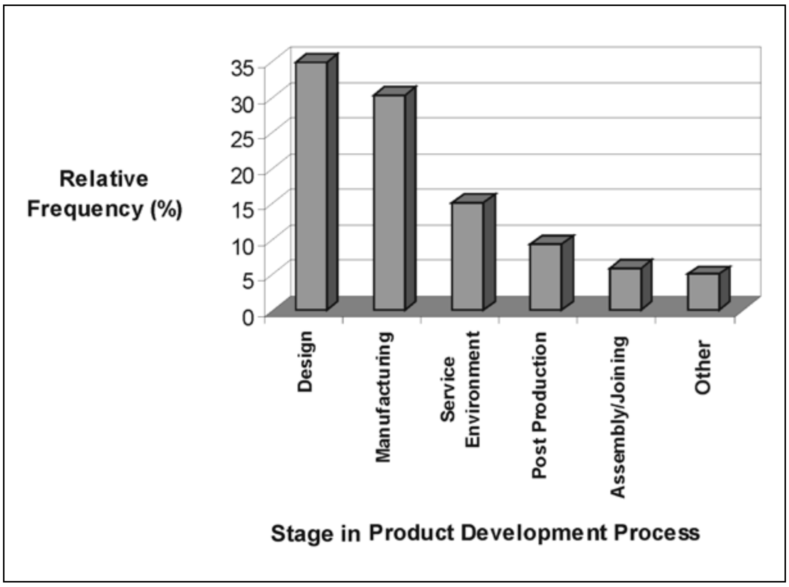

Figure 5. Stage in product development process where fatigue failures were traced

Previous figures have revealed general trends in fatigue mechanisms and their causes. It is also possible to describe the specific details of the factors that contribute to the fatigue failure of each feature classified in Figure 3. Two such features are shown in Figure 6, that concerning complex monolithic features and bolted joints. Similar charts are available for all feature types. For monolithic complex shapes the most important factor is the definition of geometry, followed by manufacturing process control and surface finish. A breakdown of the contributing factors to the fatigue of bolted joints reveals similar factors as found for complex monolithic features, in addition to the maintenance of the joint. Figure 7 describes the secondary factors that influenced the failure of two fatigue failure modes, those concerning high-cycle and corrosion fatigue. Similar charts are available for all the fatigue failure modes relevant to the cases collated. The factors that most influence high-cycle fatigue failure are geometry, manufacturing process control and marks left by manufacturing process. For corrosion fatigue failure mode, the environment and its composition along with geometry are the main factors.

With the large variety of factors contributing to fatigue failure as shown, it would be difficult for an individual to be an expert in all the disciplines needed in order to mitigate future fatigue failures in their designs. Simply collating the knowledge processed in a compendium e.g. lessons learned database, itself would not assist in the development of CDFR [26]. An alternative is to synthesise the failure process for the designer considering the most frequently occurring factors related to the feature type and failure mode as identified. Although the results are limited to the body of knowledge held about the 120 fatigue failure cases collated, the questions and supporting design, manufacture and service knowledge needed to address these factors for the appraisal of a new design can be constructed giving the necessary focus.

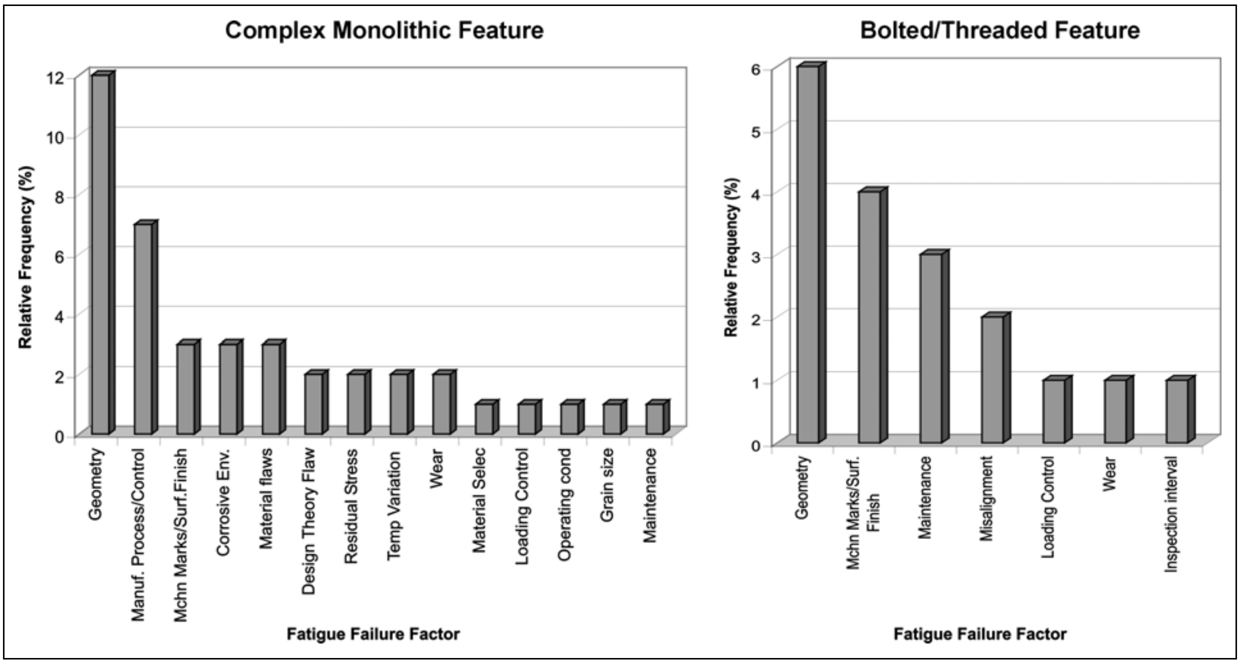

Figure 6. Fatigue factors contributing to two feature types

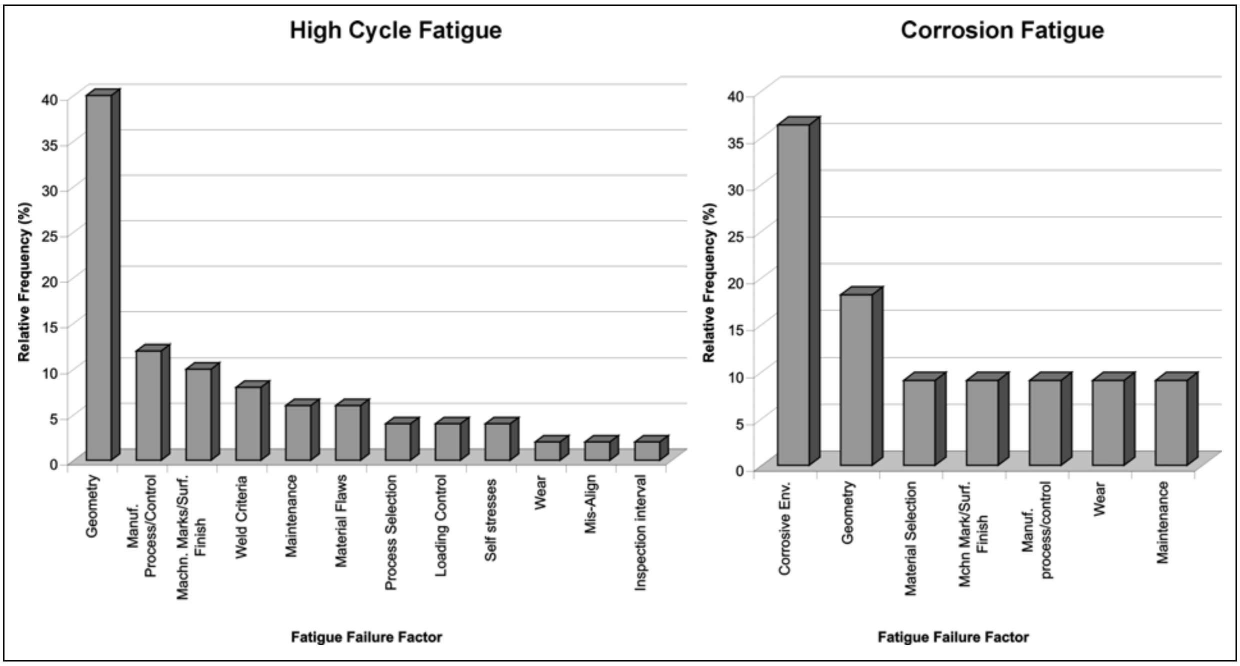

Figure 7. Fatigue factors contributing to two failure modes

5 Concept Design for Fatigue Resistance (CDFR)

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. From the issues raised by industry it has become possible to devise a capability and utility framework for CDFR, the proposed system design shown in Figure 8. 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 effect 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 [15].

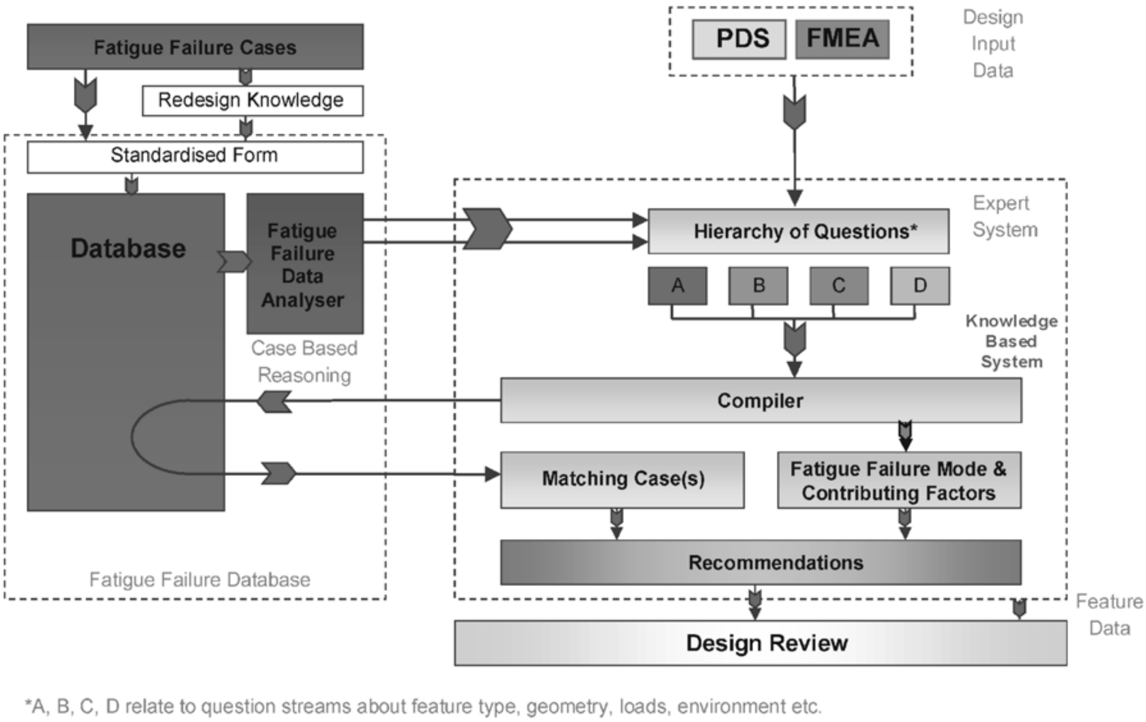

Figure 8. CDFR system design

The CDFR technique essentially becomes an amalgamation of ES, KBS and Case-Based Reasoning (CBR) methods in order that the objectives of the technique can be met. The combination of these three powerful and proven approaches, often used in isolation in failure analysis application, provides the necessary functionality for each main element of CDFR:

- ES provides specific questions, building up a detailed representation of the feature and its characteristics and then provides a diagnostic breakdown of the most probable causes or contributing factors to a fatigue failure mode(s). Confidence in the relevance of each question is provided by the fatigue failure database catalogue, which as discussed earlier, has knowledge on the contributing factors to fatigue failure modes and features from the retrospective failure cases stored.
- KBS aids the prediction of potential fatigue failure mode(s) by relating the contribution and relevance of each factor addressed by the ES to those known to contribute to specific fatigue failure mode(s).
- CBR aids the retrieval of similar fatigue failure cases, reuse the case to attempt to solve the problem, revise the proposed solution if necessary and retain the new solution as part of a new case [15, 27]. This is considered the most suitable approach for failure analysis due to the complexity of knowledge required [15].

To demonstrate how the proposed CDFR system will function, consider a feature that has been identified by FMEA with a high RPN value. The designer analyses the feature by answering a series of questions under a number of categories that aid the definition of the geometry, material, manufacturing process(es), loading situation and service environment. The answers provided at each stage are compared to specific fatigue data and knowledge about good and poor fatigue design practice in each category in order that the contributing factors to potential fatigue failure mode(s) are accrued. Confidence levels associated with the answers must also be provided to assure progress in the analysis. The technique returns the most likely fatigue failure mode(s) with a degree of confidence in addition to the fatigue factors that contributed to that failure mode(s) for the feature type. At this stage the fatigue catalogue is scanned for similar features that have failed and makes them available to the user to provide guidelines on how similar fatigue situations could have been avoided. CDFR can then output a graphical representation of confidence in the failure mode(s) predicted, the relevance of the contributing factors and finally some appreciation of the impact of the recommendations, as summarised in Figure 9. Parallel to this the user also has the experiences captured in similar failure cases that are outputted in a standard report. Confidence in the failure prognosis will be higher when a single factor or very few factors are present known to contribute to a particular fatigue failure mode. The analysis of very complex features, created by a number of manufacturing processes in sequence and high uncertainties in service conditions, etc can be mapped using the proposed system, however, confidence in the accuracy of the predictions will be reduced. Nevertheless, having a comprehensive approach as taken will raise many relevant issues for the designer or stress analyst to mitigate failure it is anticipated.

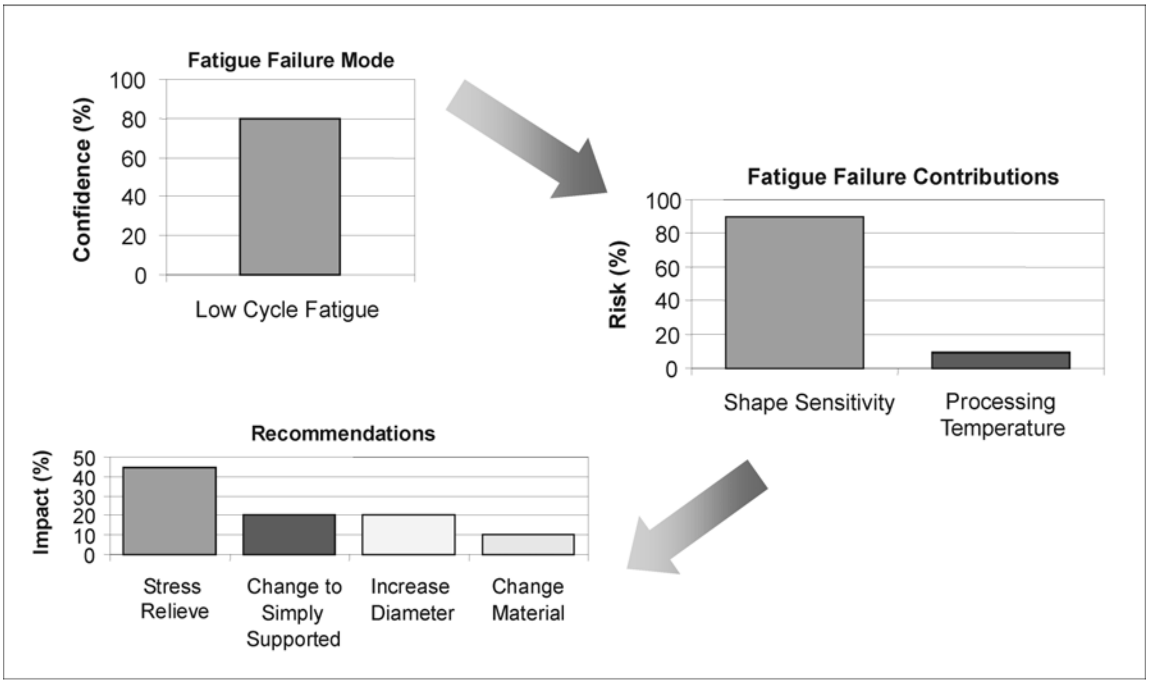

Figure 9. Proposed CDFR results and recommendations

6 Future developments

The next stage in the research is the investigation and development of the question hierarchy. Describing the key design, manufacture and service factors etc is a challenging aspect of the work, in particular balancing a limited number of questions against an appropriate level of knowledge needed for a pragmatic and rapid assessment of each feature. A similar but less complex situation was found in the development of a DFQ method called Conformability Analysis [28] and progress is being made with assistance from the industrial collaborators in this respect. The question hierarchy will also be validated for three feature types as defined by their frequency of occurrence within the current database of 120 cases, these being welds, bolted joints and complex monolithic features. Although on the face of it, the validation seems like a 'self-fulfilling' situation, this process is necessary to have confidence when applying CDFR to new designs of features. Collaborating companies are also submitting case studies to test the question hierarchy for its validity and ease of use.

If FMEA is not used routinely by a company, two other approaches are being considered to assist in the identification of features relevant to an analysis using CDFR:

- Use of a feature catalogue at the design review stage as part of the software or paper-based. Although design reviews have a low priority in the assessment of fatigue [5], this low-technology solution to the problem also requires a co-located team with a multi-disciplinary nature in order to be fully effective.
- Direct 'scanning' of CAD model to identify fatigue-initiating features rapidly. This would require interfacing the proven processes and knowledge embedded within a stand-alone CDFR system directly with a commercial CAD package. This remains a long-term goal of the research and a detailed specification will be written for the integration and adaptation of the knowledge embedded in CDFR for use in a CAD modelling system.

At present there are no accepted standards for the capturing and logging of fatigue failures and it is often the case that experts or specialists build-up knowledge with their own experiences and procedures. CDFR provides a standard template to capture new failures for inclusion in the failure catalogue. The catalogue will also assist the user who may not have much experience in failure analysis by providing fracture surface photographs and failure diagnosis advice when inputting new cases under the standard fields. This may lead to a more specific body of knowledge being accumulated by a company concerning its own fatigue failures, compared to that accumulated from the 120 general fatigue failure cases collated. It is proposed that through linkage with CBR, the failure catalogue will alter the question hierarchy providing greater relevance to those factors found to contribute to the failure cases stored by the company and related more to their specific design guidelines. Only those questions relevant to specific cases in new catalogue will be activated therefore. It is difficult to determine how many new cases in the failure catalogue are required to give the necessary confidence.

The technique devised will be restricted to the acquisition of fatigue data to a limited number of materials initially. Industrial collaborators could manage the data accumulation for other materials once confidence in the use of the technique had been established. However, many of the factors contributing to fatigue, it is contested, are applicable to many types of material classes, and therefore will be transportable between material classes when conducting and assessment of materials other than ferrous, which is the most common in engineering manufacture.

Finally, when developing new approaches and methods to support design, alignment must be found with existing practices and techniques in order to find its most effective placement in the product development process. An application framework for CDFR and existing fatigue design practice including specific methods is also ongoing [5].

7 Conclusion

Fatigue analysis accounts for a large proportion of engineering research around the world, and to many designers and engineers it is still seen as a science rather than a practical technique with which to make sound decisions on. While industry has accepted highly analytical techniques such as FEA to assist in failure prevention, some sectors feel that 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. CDFR has the potential to provide this based on initial reactions from industry, producing a ‘safety-net’ to help eliminate the most significant fatigue-initiating features from the design. A number of other benefits have also been perceived, in particular as an educational tool for inexperienced designers and engineers, who often find it difficult to perform this type of assessment [29]. It will also encourage stress analysts and designers to open up communication early in the design process before features are analysed using more comprehensive and time consuming methods by the specialist. The fatigue failure catalogue associated with CDFR provides a mechanistic way of capturing the knowledge related to new failure cases in fatigue useful in for the development of a company-specific database or to enhance Root Cause Analysis (RCA).

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References

[1] Frost, N.E., K.J. Marsh, and L.P. Pook, *"Metal Fatigue"*, Dover Publications Inc 1999.

[2] Faupel, J.F. and F.E. Fisher, *"Engineering Design: a synthesis of stress analysis and materials"*. 1981, Wiley: New York.

[3] Duga, J.J., *"The Economic Effects of Fracture in the United States"*, International Journal of Fracture, 23 (3),1983: 81-83.

[4] Osgood, C.C., *"Fatigue Design"*, Pergamon press, Oxford 1982.

[5] Darlington, J.F. and J.D. Booker. *"Designing For Fatigue Resistance: Survey of UK Industry and Future Research Agenda"*. in *IDMME*. 2003. Bath

[6] Zahavi, E. and V. Torbilo, *"Fatigue Design Life Expectancy of Machine Parts"*, CRC press 1996.

[7] Rice, R.C., ed. *Fatigue Design Handbook*. 3rd ed. 1997, SAE.

[8] Smith, R.A. *"Fatigue: A Continuing Problem Despite Its Long History"*. in *Fatigue: Real Life Solutions*. 2003. London: IMechE.1-6.

[9] Taylor, N., Current Practices for Design against Fatigue in Pressure Equipment, 2002.

[10] Tumer, I.Y. and R.B. Stone. *"Analytical Method for Mapping Function To Failure During High-Risk Component Development"*. in *ASME Design Engineering Technical Conference*. 2001. Pittsburgh

[11] Tumer, I.Y., R.B. Stone, and D.G. Bell. *"Requirements For A Failure mode Taxonomy For Use In Conceptual Design"*. in *ICED*. 2003. Stockholm

[12] McMahon, C.A., et al., *"Knowledge-Based Approach to Design for Durability in Concurrent Engineering"*, Journal of Systems Engineering, 4 (1),1994: 13-22.

[13] McMahon, C.A., et al. *"A knowledge based system for fatigue design"*. in *International Conference on Fatigue and Fatigue Thresholds*. 1990. Hawaii

[14] Leary, M. and C. Burvill, *"Resolving Complexity in Fatigue -Limited Design"*, ICED, 2003.

[15] Graham-Jones, P.J. and B.G. Mellor, *"Expert and knowledge-based systems in failure analysis"*, Engineering Failure Analysis, 2 (2),1995: 137-149.

[16] Brookes, C.A., *Personal Communication*, University of Hull, UK, August 2003.

[17] Norell, M. and S. Andersson, *"Design for Competition"*, Design for X - Concurrent Engineering Imperatives, Chapman Hall, London. 1996.

[18] Leaney, P.G., *"Case Experience with Hitachi, Lucas and Boothroyd-Dewhurst DFA Methods"*, Chapman Hall, London 1996.

[19] Carter, A.D.S., *"Mechnical Reliability"*, Macmillan, London 1986.

[20] Arajou, C.S., et al., *"The Utilization of Product Development Methods: A Survey of UK industry"*, Engineering Design, 7 (3),1996: 265-278.

[21] Jones, D.R.H., ed. *Failure Analysis Case Studies*. Vol. 1. 1998, Pergammon.

[22] Jones, D.R.H., ed. *Failure Analysis Case Studies Two*. Vol. 2. 2001, Pergammon.

[23] Esaklul, K.A., ed. *Handbook of Case Histories in Failure Analysis*. Vol. 1. 1992, ASM International. 504.

[24] Esaklul, K.A., ed. *Handbook of Case Histories in Failure Analysis*. Vol. 2. 1993, ASM International. 525.

[25] Smith, D.J., *"Reliability, Maintainability and Risk: Practical Methods for Engineers"*, Elsevier 1997.

[26] de Castro, P.M.S.T. and A.A. Fernandes, *"Methodologies for Failure Analysis"*, Materials and Design, 25 (2004),2003: 117-123.

[27] Agnar, A. and E. Plaza, *"Case-Based Reasoning: foundational issues, methodological variations and systems"*, AI Communications, 7 (1),1994: 39-59.

[28] Booker, J.D., M. Raines, and K.G. Swift, *"Designing for Capable and Reliable Products"*, Butterworth-Heinemann, Oxford 2001.

[29] Broadbent, J.E.A., *"Evaluating Concept Design for Reliability"*, ICED, (Hague),1993: 1186-1188.

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