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RESOLVING COMPLEXITY IN FATIGUE-LIMITED DESIGN

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Abstract

The design of fatigue-limited automotive components is inherently complex. Inadequate understanding and control of this complexity can result in a failure to satisfy the design requirements within the available budget or timeframe. By documenting case studies of fatigue-limited design for the automotive industry, including the authors' experience, it is intended to develop a conceptual model of the feasible product development paths for fatigue-limited design.

Investigation of the feasible product development paths generates a qualitative checklist of the major risks of design failure for a given design scenario, allowing appropriate strategies of risk management to be established before committing to a design project. Risk management strategies employed by a range of industries involved in fatigue-limited design will be identified and examined.

Keywords: Automotive engineering, planning and workflow methodology, design strategy

1 Introduction

Dynamic loading conditions range in complexity from constant amplitude loading, as occurs in rotating machinery, to complex random loading observed in wind loaded structures and vehicle suspension components [1]. If dynamic loading defines the most stringent design requirement, a component may be considered *fatigue-limited*. Fatigue-limited design is achieved by simulation and validation methods of varying sophistication and complexity [2], allowing multiple product development paths to the design of fatigue-limited components, each associated with a series of design attributes.

Fatigue limited automotive components are commonly safety-critical, where component failure directly compromises user safety and is unacceptable. Safety-critical fatigue-limited components are regularly designed and implemented within this complex and demanding industry environment.

By documenting contemporary automotive industry practices, the authors have developed a conceptual model of the feasible product development paths for the design of safety-critical fatigue-limited components. The product development paths observed in a range of industries have been documented, including a detailed case study of the authors' industrial experience. The product development paths were then analysed in terms of design complexity and the risk and consequences of failure, leading to a qualitative checklist of efficient means to reduce design uncertainty and providing techniques for risk reduction of safety-critical fatigue-limited design projects against known design resources and implementation schedules.

When faced with changing design constraints and objectives, the optimal design solution shifts, leading to a new optimal point [3]. The sensitivity of part deployment time and development cost to such changes has been investigated for various stages of the design process. The implications of this study to fatigue-limited design programs are discussed.

2 Contemporary industry design practices

Relevant case studies were identified in the literature and selected on the basis of company size, type and design history in order to gain insight into a disparate range of product development paths. Design case studies were reviewed and the product development paths documented for the following industry types:

- An established component design and supply bureau commissioned by an automotive manufacturer [4];
- An automotive manufacturer developing a component internally [5];
- A component manufacturer and design bureau engaging in freelance component redesign for an automotive manufacturer [6], and;
- A component manufacturer with little design history providing freelance component redesign to an automotive manufacturer [7].

The product development paths were analysed to identify common elements of the design process as well as individual differences in design strategy and experience. Relevant elements of the product development paths include [8]:

- Design requirements;
- Material properties;
- Durability estimation;
- Laboratory testing, and;
- Product proving.

2.1 Design requirements

Suspension components are subject to actual operating conditions that are beyond the influence of the manufacturer [9]. These poorly defined operating conditions must be distilled to a precise set of design requirements that form the basis for assessing concept feasibility and defining component geometry and material properties. Design requirements for fatigue-limited cases generally consist of discrete loading conditions and a minimum durability for each anticipated loading condition (e.g. cornering fatigue, panic braking and vehicle impact). Three methods are currently used to define the design requirements:

- a design precedent deemed by the manufacturer to prove the durability of a component to an acceptable level;
- service loading experimentally measured from similar components used as a basis for the component under development, or;
- theoretical evaluation of component loading.

2.2 Material properties

Dynamic material properties useful to fatigue design are obtained from specimens designed to represent baseline material properties of the intended material. Such tests may be either stress or strain controlled, as required by the method of durability analysis. Generic material properties may be obtained from literature sources, however, data is relatively scarce and testing and reporting procedures are non-standard [10]. The generation of explicit data is expensive and time consuming and generally reserved for cases that necessitate precise data, such as the use of novel materials or investigation of unexpected failure.

2.3 Durability estimation

Based on material properties and geometry, the durability of the component is predicted theoretically. Computer based analysis techniques such as Finite Element Analysis (FEA) provides accurate stress and strain conditions for complex components under a given loading, however the material response to dynamic loading is not always precisely understood [8].

2.4 Laboratory testing

Due to the uncertainty of fatigue lifetime prediction techniques, it is common to confirm the durability estimation by testing a physical model subjected to the design specifications on which the durability analysis was based. Laboratory testing ranges in complexity, and may include single or multiple axis test apparatus. Such testing may be performed on a prototype that emulates the final production component, but is manufactured by methods more suited to low volume production [4].

2.5 Product proving

Before a component is approved for production, a final prototype must be tested under end-use conditions. Product proving verifies the correctness of the simplifications made in defining the design requirements [9]. Product proving may be performed by testing a complete vehicle on a proving ground circuit, by simulating prerecorded vehicle inputs under laboratory conditions or by a combination of both methods.

Notable attributes for each design case study are documented in Table 1.

Table 1. Product development paths for a range of automotive design case studies

Company Type	**Design Scenario**	**Material Properties**	**Material Properties**	**Design Requirements**
Automotive Manufacturer (**A**), Design and supply bureau (**D**) or Component manufacturer (**C**)	Internal (**I**), Commissioned (**C**), or Freelance (**F**)	Actual (**A**) or Generic (**G**) material properties	Novel Material? Yes (**Y**) or No (**N**)	Design requirements modified? Yes (**Y**) or No (**N**)
D [4]	C	A	Y	N
C [7]	F	G	Y	Y
A [5]	I	A	N	N
D [6]	F	?	Y	Y

Table 1. Product development paths for a range of automotive design case studies (continued)

Company Type	**Design Scenario**	**Laboratory Test**	**Product Proving**	**Design Implementation**
Automotive Manufacturer (**A**), Design and supply bureau (**D**) or Component manufacturer (**C**)	Multiple product development paths? Yes (**Y**) or No (**N**)	**P**roduction component, or low volume **M**ock-up	Proving ground (**P**) or Laboratory Simulation (**L**)	Component implemented? Yes (**Y**) or No (**N**)
D [4]	Y	M	P/L	Y
C [7]	N	M	P	N
A [5]	?	P	P/L	Y
D [6]	N	P	P	Y

2.6 Product development paths

Reviewing the product development paths employed in a range of automotive design projects allowed the authors to develop a generalised conceptual model for the design of safety-critical fatigue-limited components (Figure 1). Product development paths consist of the elements defined earlier, with links fashioned to correspond to the constraints and objectives of fatigue-limited design for automotive applications (Table 2).

Table 2. Typical design objectives and constraints for fatigue-limited automotive component design

Objectives	• Minimise cost • Minimise mass
Constraints	• In service failure must be avoided • Implementation schedule • Design budget • Spatial constraints, due to assembly and component interaction

To satisfy component durability while meeting time constraints, design practices for fatigue-limited automotive components include two nested design paradigms: *design-test-build* and *design-build-test* [11] (Figure 1). The design-test-build loop involves theoretical analysis of design durability based on the component geometry and material characteristics. FEA is employed to identify critical regions and to suggest geometry modifications to correct problem areas. Based on this simulation, design engineers predict the suitability of a virtual prototype to satisfy the design requirements. For example, if the design requirements can not be satisfied with the specified material, the inputs to the durability analysis are examined and the design process reiterated. It may be possible to reassess the design with a more fatigue resistant material, or to modify the associated design requirement (Section 4). If neither of these conditions can be satisfied, the project is deemed infeasible. It is possible for the complexity of the design requirements to exceed the capacity of the durability estimation. Mismatch between design requirement complexity and analysis capability can be allowed for by increasing the safety factor.

The design-test-build loop provides a rapid estimate of component durability and feasibility, but contemporary fatigue life estimation is not of guaranteed accuracy and requires confirmation by laboratory testing [8][9]. All industries surveyed applied some process of laboratory testing based on the design requirements to verify the theoretical analysis. Two of the industries performed verification testing on a prototype that emulated a final production component, but was manufactured by methods suited to low volume production (Table 1). Such a strategy can be useful if the design budget is limited [7], or the final production machinery is not yet available or pending successful initial trials [4]. Component failure at the laboratory test stage indicates error in the durability analysis, necessitating reiteration of the design-test-build loop with increased safety factors, or by identifying and resolving the source of error.

If laboratory testing confirms the correctness of the durability analysis, the component enters the design-build-test loop. The objective of which is to confirm the correctness of the initial assumptions made in defining the design requirements by testing the component under end-use conditions. For the case studies reviewed in this paper, all laboratory tests were performed in-house, but only the automotive manufacturers had facilities suitable for product proving. Product proving is the final design check before the component is implemented into production and requires components of final production quality. Failure at the product proving stage implies that the design requirements do not adequately represent the loading conditions and necessitates a complete reiteration of the design process, potentially having an associated failure to satisfy time or budget constraints.

In order to mitigate risk of a failure at the product proving stage, one manufacturer involved in novel material substitution simultaneously developed an equivalent component from traditional cast iron. It was not until the novel design had passed product proving that development of the cast iron component was concluded [4]. This design safety net is often implemented by automotive designers working on non-trivial design tasks with an inelastic delivery date. A technique employed by Toyota is termed *parallel set narrowing*, in which multiple designs are developed concurrently until a clearly optimal solution is found [11]. The development of multiple designs mitigate the risk of failure to satisfy the design requirements within the available time, but can only be achieved with significant increase in design cost.

Another condition that necessitates iteration of some elements of the design process is associated with modifying the design requirements (Figure 1). Such *shifting specifications* require the design project to regress to the initial stage of design requirement definition. The consequences of which depend on the level of progression through the design process and the subsequent effort required to satisfy the modified design requirements. Two of the four case studies investigated involved shifting specifications (Table 1). Common features of both cases are:

- The redesign involved a novel material substitution;
- The design was developed freelance by a group outside the vehicle manufacturer, and;
- The design requirements were modified after the presentation of a successful prototype to the automotive manufacturer.

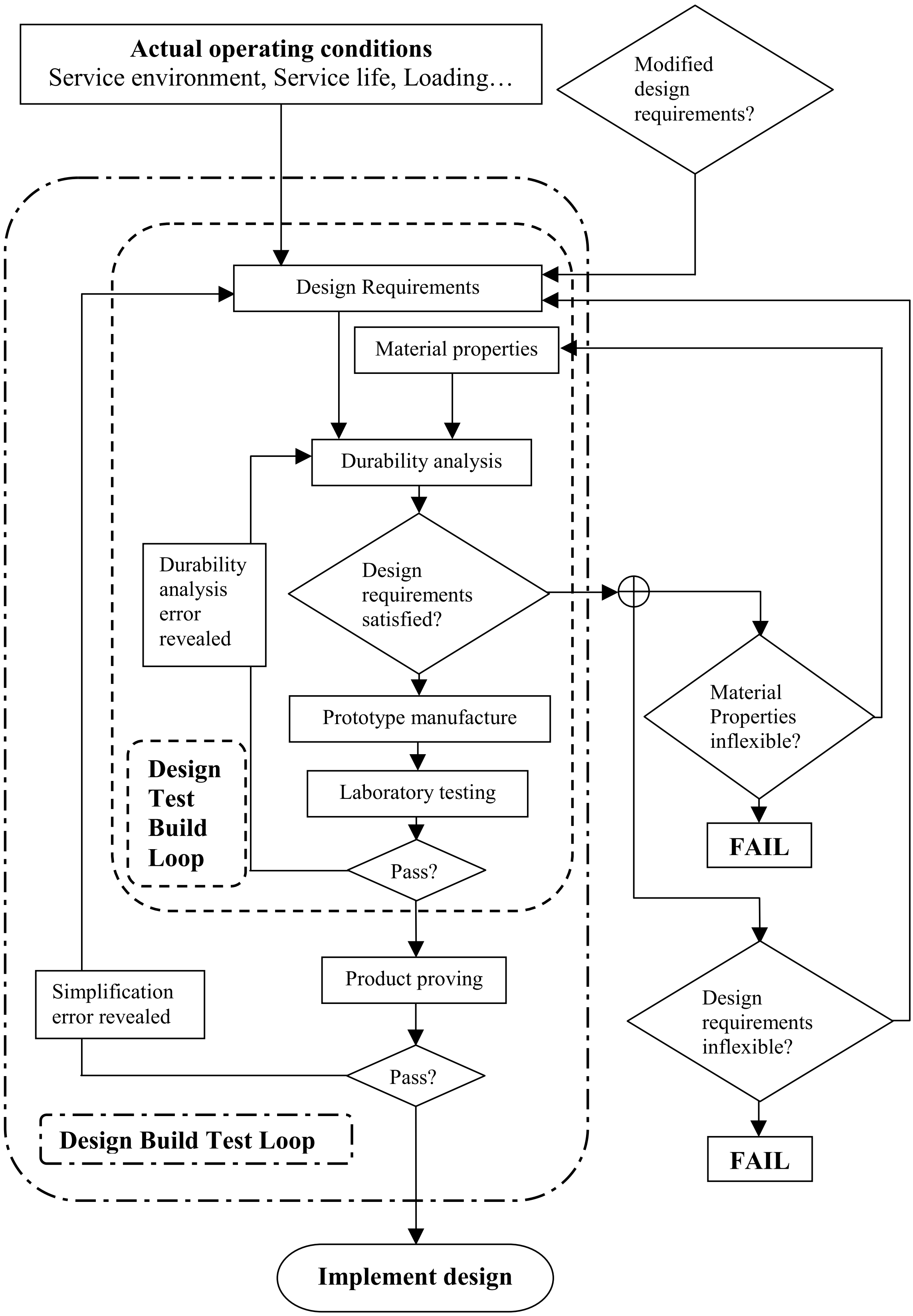


Figure 1. Generic product development path for fatigue-limited safety-critical automotive components

2.7 Consequence of failure

The generic product development schematic (Figure 1) includes four *failure conditions* that demand iteration of some element of the product development path (Table 4). Iterations necessitated by each failure condition have been evaluated in the case study (Section 3), defining the penalty associated with each failure condition in terms of individual element costs (Table 3).

The failure penalty increases as product development advances. The cost associated with each element varies significantly and is dependent on the specific design scenario. Estimating the failure penalties for an intended fatigue-limited design provides a qualitative indication of the relative risk of each element of the design process, allowing appropriate risk management strategies to be implemented.

3 Fatigue-limited design case study

This case study documents the authors' experience in the design of a fatigue-limited, safety-critical automotive component. The project was developed with a collaborative industry partner. As the industry partner had little experience in component design, it was decided to verify the intended design method with an initial project of limited scope and budget. The selected project was to satisfy the steering arm fatigue test of a steel steering knuckle that had, until recently, been supplied to an automotive manufacturer by the industry partner. The industry partner identified an opportunity to secure ongoing supply contracts by developing an equivalent lightweight aluminium substitute component.

Preparation for component design included a literary survey of previous design experiences (Sections 1 and 2), an internal audit of the relative cost of each element of the design process, and an estimate of the penalty associated with each failure condition (Tables 3 and 4).

Table 3. Estimated element cost for the steering knuckle development

Design element		**Cost[1] for case study**
Design requirement development,	C_r	5
Durability analysis,	C_d	20
Prototype manufacture,	C_m	100
Laboratory testing,	C_t	20
Product proving,	C_p	Nil[2]

The existing geometry was analysed using FEA software. An iterative process of geometry modification led to a geometry that was acceptable for the available substitute aluminium material. Major geometry modifications included the modification of the lower attachment point and increased arm geometry (Figure 2). The FEA analysis gave confidence that the design requirements could be met by the proposed aluminium component, however, the design team (the authors) realised that the original design requirements may not be suitable for an aluminium component [6]. The failure condition analysis (Table 4) identified a significant increase in failure penalty if the laboratory test failed, and that a limited design

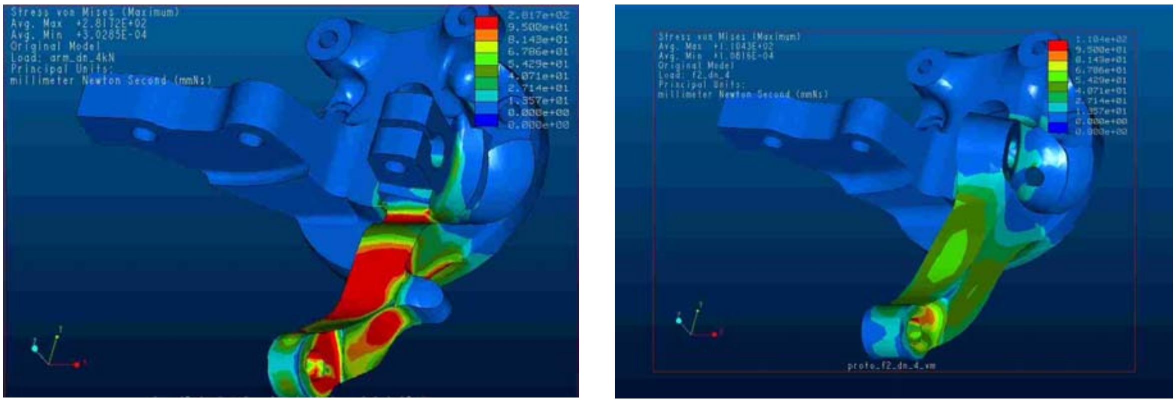
[1] Estimate of relative design effort based on case study experience. Capital costs not included.
[2] Product proving cost to be borne by the automotive manufacturer.

budget precluded the manufacture of multiple physical models. In order to provide a buffer against unexpected modifications to the design specifications, the safety factor was increased.

Table 4. Potential failure points for the steering knuckle development

Risk level	Failure condition	Failure penalty	Case study penalty
1	Unsuccessful product proving	$= C_r+C_d+C_m+C_t+C_p$	= 145
2	Modified design requirements	$\leq C_r+C_d+C_m+C_t+C_p$	≤ 145
3	Unsuccessful laboratory test	$= C_r+C_d+C_m+C_t$	= 145
4	Design requirements or material requires modification	$= C_r+C_d$	= 25
5	Unable to satisfy design requirements	= FAIL	= FAIL

To reduce the cost of prototype manufacture, the prototype forging dies were modified from those used to forge the original steel component. Twenty prototype components were forged. Unanticipated differences between the forming characteristics of steel and aluminium led to defects in the aluminium prototypes that would not be acceptable in a production component. Even with this limitation, the prototype components satisfied the design requirements in laboratory testing. Shortly after presenting the test outcomes to the automotive manufacturer for review, the design load was increased by 12.5%. The earlier decision to allow a contingency for unanticipated changes of this type meant the aluminium prototype satisfied the modified design requirements.



Original steel component   Aluminium prototype

Figure 2. Von Mises stress for FEA of steering arm fatigue test

The success of the initial design led to the project scope being increased to include two more function tests: cornering fatigue and panic braking. FEA analysis of the aluminium prototype indicated that the ability of the aluminium design to accommodate the cornering fatigue test was questionable and that the panic braking test could not be accommodated without significant modification to the McPherson strut attachment point. To minimise uncertainty regarding the prototype's ability to meet the cornering fatigue tests, four prototypes were tested. The prototypes fell short of the design minimum by approximately 20%. Review of the failed components resulted in focused design change suggestions to meet the cornering fatigue test at the next design iteration. At present, the aluminium design concept is not feasible unless the design requirements can be modified to allow changes to the attachment point of the McPherson strut. This decision is the responsibility of the automotive manufacturer.

4 Results and key conclusions

The design of safety-critical fatigue-limited automotive components is inherently complex. Incorrectly allowing for this complexity can result in a failure to satisfy the design requirements within the available budget or timeframe. Examining the intended product development path (Figure 1) can reduce the potential failure risk of a design. Combining estimates of the relative elemental costs (Table 3) with the associated failure penalties (Table 4) generates a qualitative checklist of the major risks of design failure for a given scenario, allowing appropriate strategies of risk management to be established before committing to a design project.

Appropriate methods of risk management are dependent on the available resources and design time. The dominant design constraint for:

- automotive suppliers is an inflexible design schedule imposed by automotive manufacturers, and;
- freelance design bureaus is a relatively limited design budget.

Either case leads to different methods of mitigating the risk of design failure, including: design iteration, safety factor dilation and the application of multiple product development paths.

Analysis of the steering knuckle design project identified failure to meet laboratory tests as the major source of risk. To mitigate the consequence of prototype failure, and to pre-empt the potential for modified design requirements, the design safety factor was increased. This decision was justified when the component passed laboratory testing despite the design performance requirements being increased after prototype manufacture.

An increased safety factor can lead to the overdesign of a component. Overdesign may be progressively reduced by iteratively optimising the design over successive models using the same underlying platform. Another strategy is the application of multiple product development paths, thereby providing a safety net against design uncertainty, however, this approach multiplies development costs. The literature suggests that the multiple development path approach is mostly used by large industries with design specifications dominated by implementation time. Smaller enterprises with limited budgets employ an iterative approach. If iteration is not allowable, optimisation is compromised for design expediency by increasing the design safety factor.

Shifting specifications have the potential to be as costly as failure to meet product proving and can occur without warning. Case study research indicates that industries particularly exposed to such risk are those embarking on freelance design that has not been directly commissioned by the automotive manufacturer [6][7] (Table 1).

The case study presented involved the application of a novel material. That specifications shifted after presentation of a prototype that successfully met the required laboratory tests suggests that the end user (automotive manufacturer) was not initially mindful of the implications of novel material substitution to the design requirements. The potential damage associated with shifting specifications can be reduced by entering a formal agreement on design requirements with the end user at the outset, or by incorporating additional safety factors to guard against unexpected changes.

When faced with changing design objectives and constraints, the optimal design solution shifts, leading to a new optimal point [3]. A case study has been presented that focused on mass reduction for safety-critical fatigue-limited suspension components [4][6][7]. This paper has explored issues associated with design complexity, and has offered strategies to assist the designer identify and resolve critical issues, minimising associated risk.

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