

Evaluating the Impact of Conservatism in Industrial Fatigue Analysis of Life-Limited Components

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Abstract. This paper presents a review of the conservatism approaches applied by different industrial sectors to the stress-life (S-N) analysis of ‘life-limited’ or ‘safe-life’ components. A comparison of the fatigue design standards for 6 industrial sectors identified that the conservatism approaches are highly inconsistent when comparing the areas of variability and uncertainty accounted for along with the conservatism magnitude and method of application. Through the use of a case-study based on the SAE keyhole benchmark and 4340 steel S-N data, the industrial sector which introduces the greatest reduction of a component life-limit was identified as the nuclear sector. The results of the case-study also highlighted that conservatism applied to account for scatter in S-N data currently provides the greatest contribution to the reduction of component life-limits.

1 Introduction

Across the different engineering sectors (e.g. aerospace, nuclear, offshore, etc.), many life-limited components are designed against fatigue failure using analysis methods comprising of stress-life (S-N) curves and Miner’s Rule [1]. This approach to fatigue design and analysis is also known as ‘safe-life’ [1]. The ‘safe-life’ or ‘life-limit’ of a component represents the number of duty cycles after which the component must be removed from service [1].

Fatigue design of life-limited components contains significant areas of variability and uncertainty. ‘Variability’ is defined as the ‘randomness’ or scatter that can be observed within fatigue design parameters, resulting from the probabilistic nature of fatigue [2]. ‘Uncertainty’ is defined as the lack of knowledge or assumptions required about a specific element of the S-N analysis process [2]. This variability and uncertainty propagates through the analysis process, resulting in significant variability and uncertainty in a component’s life-limit [1]. In order to account for this variability and uncertainty, and to ensure components retain their structural integrity in-service, conservatism is currently applied within the analysis process [1]. This conservatism effectively reduces the life-limit of a component and often takes the form of statistical reductions on material properties or as ‘safety factors’ [1]. The conservatism required during design is usually prescribed in the relevant design standards for each industrial sector.

This paper will compare the different approaches to conservatism used by various industrial sectors when

analysing life-limited components. In addition, the impact of each conservatism approach on the life-limit of a component will be evaluated using a case-study.

1.1 Justification for Investigating the Impact of Conservatism

Investigating the impact of conservatism on component life-limits during fatigue design provides the opportunity to compare the conservatism approaches used in various industrial sectors. This includes a comparison of: the areas of variability and uncertainty accounted for, the method of conservatism application and the magnitude of the conservatism currently required. The introduction of conservatism into the analysis process can lead to the potential life of a component not being fully exploited due to retiring a component from service at an earlier life-limit. Conservatism can also result in components being ‘over-sized’ and heavier, increasing the total life-cycle cost of a component and reducing the overall performance of the structure [1]. By comparing the conservatism approaches applied by various industrial sectors to the S-N fatigue analysis of life-limited components, it will be possible to identify which industrial sectors introduce a significantly greater magnitude of conservatism. For sectors that are shown to be more conservative, an investigation into areas of conservatism that could be reduced can be initiated, potentially resulting in more efficient components with longer life-limits, which remain safe and reliable in-service.

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1.1.1 Previous Literature Comparing Industrial Conservatism Approaches

Previous studies that compare the conservatism approaches within different industrial sectors have been identified within the literature. Work performed by Micone & De Waele compared the safety factors and statistical reductions on material properties across various design standards relating to the fatigue design of steel structures and offshore structures [3]. However, they concluded [3] that the conservatism approaches were not comparable and therefore, it was not possible to identify whether one fatigue design standard was more conservative than other. This paper aims to further their work by quantifying the impact on a component life-limit of the various conservatism approaches through the use of a case-study. Fatigue design standards for the offshore industry and nuclear industry have also been qualitatively compared in [4] and [5] respectively. However, to the authors' knowledge there is yet to be a comparison of the conservatism approaches from fatigue design standards across various industry sectors. This paper aims to contribute to this gap in the literature by comparing the aerospace, nuclear, wind turbine, offshore and steel structures sectors.

1.2 Included Industrial Sectors

Table 1 shows the different industrial sectors reviewed, along with the supporting design standards, advisory material/industrial practice and typical examples of life-limited components. References from the literature for each sector are also shown.

Other industrial sectors that could have been included within this review were the automotive sector [1] and the rotorcraft sector (e.g. helicopters) [6]. All of these sectors feature fatigue critical components due to high cyclic loading. Unfortunately, insufficient literature in the public domain was available in the time-frame of this work to identify the conservatism used by these industries.

1.3 Scope of Paper

In order to enable a comparison across the different industrial sectors, which often have different fatigue design drivers based upon the loading and consequence of failure of the component, the scope of this paper has been focused in a number of ways. This sub-section defines the scope of this paper.

1.3.1 Component Characteristics

The design standards shown in Table 1 represent a wide range of potential component and material types. Therefore, a 'common' component must be defined that is applicable to each of the design standards. This component has been identified to be a 'life-limited', single-load path and monolithic (i.e. no weldments) component manufactured from high-tensile strength steel, that is not inspected in-service. Whilst this is a simple component compared to the welded components that feature heavily in the offshore and nuclear sectors [11, 13], it does represent the typical characteristics of an aircraft landing gear component [6].

1.3.2 Stress-Life (S-N) Fatigue Analysis

The scope of this paper has also limited the analysis methods to be considered. The fatigue analysis method for life-limited components that is consistently represented across the various design standards is a stress-life (S-N) approach to fatigue analysis. Whilst many of the design standards provide alternative routes to fatigue certification, such as a fracture mechanics approach, this is beyond the scope of this paper and therefore, only an S-N approach will be considered. In addition, there are subtle differences in the S-N analysis methods prescribed in each design standard (e.g. the mean-stress correction required). However, as this paper is concerned with the impact of the conservatism approach on a component's life-limit, a 'common' S-N fatigue analysis process has been defined. As S-N fatigue analysis is a 'traditional' and well-known analysis approach, a detailed description of the method can be found in many textbooks (e.g. [1]). The common S-N fatigue analysis process is defined as follows:

- 1) The load spectrum is converted into load cycles '*i*', comprised of a load amplitude and mean load using rainflow counting.
- 2) Analytical stress analysis is used to convert the loads into a stress amplitude (σ_{a_i}) and mean stress (σ_{m_i}).
- 3) The Goodman mean stress correction is used to convert the stress cycles into fully-reversed (i.e. $\sigma_m = 0$) stress amplitudes (σ_{s_i}).
- 4) From a mean S-N curve, which indicates how the number of cycles to failure varies with the applied fully-reversed stress amplitude, the number of cycles to failure (N_{f_i}) for each applied stress cycle

Table 1. The industrial sectors included within this paper and supporting references.

Industrial Sector	Design Standard	Advisory Material	Typical Components
Large Aircraft	EASA CS25 [7]	EASA AMC25 [7]	Aircraft Landing Gear [6, 7]
Light Aircraft	FAA Part 23 [8]	FAA AC23 [8]	Fuselage and Wing Structures [8]
Nuclear	ASME III NB [9]	ASME III NB [9]	Piping and Boilers [9]
Wind Turbines	BS61400-1 [10]	-	Turbine Blades, Hubs, Towers [10]
Offshore Structures	DNVGL-RP-C203 [11]	DNVGL-OS-C101 [12]	Offshore Platforms, Jackets and Piles [11]
Steel Structures	Eurocode 3 [13]	-	Steel Bridges [13]

is identified.

- 5) Using Miner’s Rule, the damage accumulated for each applied stress cycle (d_i) is computed.
- 6) The total damage accumulated for the loading spectrum (D_T) is computed as the sum of the individual damages ‘ d_i ’.
- 7) The life-limit (i.e. the number of loading spectrum applications to failure) of the component is computed (assuming failure occurs when $D_T = 1$):

$$Life\ Limit = \frac{1}{D_T} \quad (1)$$

When using a mean S-N curve, this infers that half of the components manufactured will have failed at a damage value of 1.

2 Methods of Introducing Conservatism into S-N Fatigue Analysis

There are a number of distinct methods that enable conservatism to be introduced into the S-N fatigue analysis of life-limited components. These methods can be differentiated into statistically-derived reductions and single-value (i.e. ‘deterministic’) reductions. Deterministic reductions will be referred to as ‘safety factors’ for the remainder of the paper. The first of the conservatism application methods is to apply a safety factor directly to the computed component life-limit. The application of this conservatism results in the component only being permitted to be in-service for a design life equal to the life-limit as computed using S-N analysis divided by the safety factor. A similar approach is to divide the Miner’s Rule failure criterion (which is typically taken as $D_{fail} = 1$) by a safety factor. Another method of applying conservatism is to use a safety factor on the applied stress amplitudes. The final method of application is to modify the S-N curve from the mean S-N curve that would be fitted to S-N data. This reduced curve is typically known as a ‘design’, ‘working’ or ‘characteristic’ curve. This reduction can either be achieved by dividing the stress amplitude or the number of cycles to failure (i.e. a factor on ‘life’) for the mean curve by the selected safety factor. These factors shift the S-N curve ‘down’ and ‘left’ respectively. Figure 1 presents a flowchart that demonstrates how conservatism is applied at the different stages of S-N fatigue analysis.

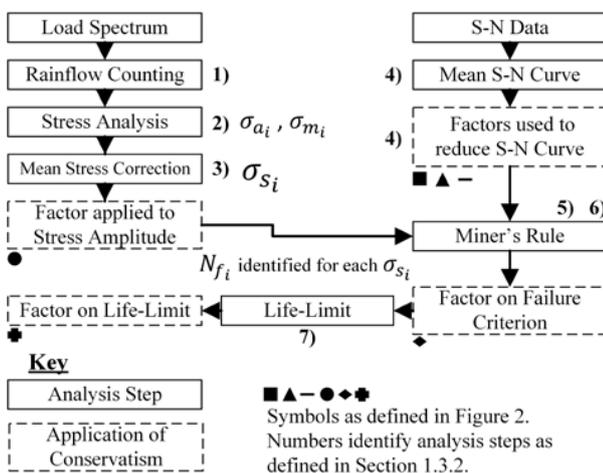


Figure 1. A flowchart showing the S-N fatigue analysis stage at which each conservatism method is applied.

2.1 Statistical Reduction of S-N Curves

The final approach for introducing conservatism into S-N fatigue analysis is through applying statistically-derived reductions to the S-N data to produce design curves. These curves are typically defined using a Probability of Survival (PoS) and a Confidence Level (CL). For a set of S-N data the PoS value represents the proportion of specimens that would be expected to survive at a given stress level.

If the number of cycles to failure (or the logarithm of cycles to failure) are Normally distributed, tables exist [14] for identifying the statistical reduction factor ‘ $k_{PoS/CL}$ ’ (for the desired PoS/CL level) that computes the reduced number of cycles to failure ‘ $N_{PoS/CL}$ ’ using:

$$N_{PoS/CL} = \bar{N}_f - (k_{PoS/CL} \times S) \quad (2)$$

where ‘ \bar{N}_f ’ is the mean number of cycles to failure from the S-N dataset at a given σ_{si} and ‘ S ’ is the sample standard deviation of the number of cycles to failure at the same σ_{si} . As ‘ \bar{N}_f ’ and ‘ S ’ are estimates of the population based on the sample data, they must be stated with a level of confidence and this is captured by the CL value. It should be noted that a PoS/CL value of 50/50 represents the mean S-N curve.

3 Qualitative Comparison of Industrial Conservatism Approaches

A comprehensive review of the fatigue design standards for each industrial sector from Table 1 enabled the population of the matrix shown in Figure 2. Each populated cell in Figure 2 permits the identification of the area of variability and uncertainty accounted for by each conservatism approach, along with the method of application and the magnitude of the conservatism approach for each industrial sector. From reviewing the matrix in Figure 2, qualitative comparisons regarding the three elements of the conservatism approaches listed above can be drawn across the different industrial sectors.

Firstly, the areas of variability and uncertainty accounted for vary significantly across the industrial sectors. The only area consistently accounted for is scatter within S-N data, as shown by the fully populated row in Figure 2. Most sectors, excluding nuclear and steel structures, also account for deviations in the loading applied to a component. The large aircraft, wind turbine, offshore and steel structures sectors all account for the consequence of failure of a component using conservatism. It is interesting to note that despite the widely discussed uncertainty present within the assumptions of an S-N approach based upon Miner’s Rule [1, 2], only light aircraft structures and offshore structures apply conservatism that directly accounts for uncertainty within analysis methods. The conservatism approach used by the wind turbine sector appears to be the most comprehensive approach by being the only sector to use conservatism to account for: dimensional

		Industrial Sector					
		Large Aircraft (EASA CS25) [7]	Light Aircraft (FAA Part 23) [8]	Nuclear (ASME III NB) ^A [9]	Wind Turbines (BS61400-1) ^B [10]	Offshore Steel Structures (DNVGL-RP-C203) [11, 12]	Steel Structures (Eurocode 3) [13]
Area of Variability or Uncertainty							
Materials Data	S-N curve material scatter	■ 99/95	+	■ 2* ▲ 2	■ 97.7/95	■ 97.7/75	■ 95/75
	Deviation of properties from design data				● 1.1*		
	Difference between coupon/specimen used to generate S-N curve and component	+	+		● 1.1*		
	Effect of surface finish and material treatment			■ 2* ▲ 4*			
	Size effect			▲ 2.5			
	Environmental degradation / no environmental protection applied to component	+		■ 2* ▲ 4*			
Loading	Deviations in applied loads from those assumed during analysis / uncertainty in loading	+	+		● 1 ^C	◆ 10 ^{*E}	
	Accuracy of stress concentration factors		+				
Geometry	Variability or uncertainty in geometrical properties (e.g. manufacturing tolerances)				● 1.1*		
	Inaccurate assessment of component resistance (e.g. structural sections)				● 1.1*		
Component	Consequence of failure for component / level of required safety	+			● 1.15 ^D	◆ 10 ^{*E}	■ 1.35 ^F
	Inspectability of components					◆ 10 ^{*E}	
Analysis	Uncertainty in analysis methods		+			◆ 10 ^{*E}	
	Uncertainty in conversion factors				● 1.1*		

- A: Only the most conservative of either the "stress" factor or "life" factor on the S-N curve is applied.
- B: Assuming Steel material (other conservatism values are provided for other materials).
- C: This conservatism is used to account for loading uncertainty and deviation during static design.
- D: Class 2 "non fail-safe" components whose failure may lead to the failure of a major wind turbine part.
- E: Either a multiplication of the accumulated damage or as a divisor on the Miner's rule failure criterion.
- F: Required for a safe-life component (i.e. non inspected) with a high consequence of failure.

Figure 2. A matrix showing the different conservatism approaches used by various industrial sectors, including the areas of variability and uncertainty accounted for, the method of conservatism application and the magnitude of the conservatism applied.

variability (e.g. manufacturing tolerances), deviations from anticipated material properties and differences between the tested specimens and the final component. The ASME III nuclear conservatism approach accounts for material properties beyond other sectors, such as surface finish effects and size effect. Figure 2 shows that Eurocode 3 steel structures account for the fewest areas of variability and uncertainty, only using conservatism to account for S-N data scatter and the consequence of failure.

As most of the areas of variability and uncertainty shown in Figure 2 are common to fatigue design, regardless of application/industrial sector, these findings suggest that 'lessons learned' could be shared between the different sectors, to ensure that each industrial sector is accounting for all potential areas of variability and uncertainty within fatigue design. For example, most of the industrial sectors could introduce conservatism to account for uncertainty in analysis methods.

Concerning the method of application of conservatism, there is little consistency across the industrial sectors. As can be seen in Figure 2, large aircraft employ both a PoS/CL curve with a safety factor on the life-limit, whereas light aircraft structures only use a safety factor on life-limit to introduce conservatism. The offshore sector uses a PoS/CL curve and a safety factor on the value of Miner's Rule failure criterion (known as a Design Fatigue Factor – DFF [11]). The wind turbine sector introduces yet another approach for introducing conservatism, using a PoS/CL curve and a safety factor on the applied stress amplitude. It is interesting to note that the ASME III approach for nuclear components applies the most conservative out of a deterministic stress or life factor on the mean S-N curve. Finally, steel structures under Eurocode 3 use a stress factor on the statistically reduced PoS/CL S-N curve. It can be seen that there is significant

inconsistency in the method used to apply conservatism across the industrial sectors.

The methods of conservatism application also vary considerably for each individual area of variability or uncertainty. For example, Figure 2 shows that S-N data scatter is accounted for using statistically reduced PoS/CL S-N curves, deterministically reduced S-N curves as well as a safety factor on the component life-limit. Likewise, deviations in applied loading is accounted for using: a safety factor applied to the stress amplitude, a safety factor applied to Miner’s Rule failure criterion or using a safety factor on the component life-limit. Figure 2 also shows that often a conservatism method is used that does not directly address the origin of the area of variability and uncertainty being accounted for. For example, the wind turbine sector uses a safety factor on the stress amplitude to account for deviations in the materials data, which one would expect to be accounted for using conservatism applied to material properties directly. This discussion has shown that the methods of applying conservatism are highly inconsistent across the industrial sectors.

On the other hand, one area of consistency regarding the conservatism methods is the use of PoS/CL S-N curves, as these are used by the majority of industrial sectors. However, as Figure 2 shows, different sectors use different PoS/CL levels. In order to demonstrate the impact of applying conservatism to S-N curves, a rich S-N dataset for 4340 Steel (typical of the high-tensile strength steel used in landing gear components [6]) was sourced from the Engineering Sciences Data Unit (ESDU) [15]. Two significant challenges exist when working with S-N data. Firstly, steels exhibit a fatigue limit ‘ σ_{FL} ’ - an applied cyclic stress amplitude that could theoretically be applied indefinitely without fatigue failure. As Miner’s Rule assumes $d_i = 0$ for such stress amplitudes, the σ_{FL} must also be statistically reduced to the desired PoS/CL level using the same method as for $N_{PoS/CL}$ (shown previously in Equation 2). The mean and sample standard deviation of the fatigue limit was calculated using the ‘Probit’ method as described by Schijve [2]. Secondly, S-N data typically contains ‘run-outs’ where the fatigue test is stopped at a pre-defined number of cycles, even if the specimen has not failed. As run-outs require complex statistical treatment, which is beyond the scope of this paper, these data points were omitted, and the sample Coefficient of Variation (CoV) was assumed to be constant for all stress levels that demonstrated run-outs. The CoV for S-N data is shown in Equation 3 [1].

$$CoV = \frac{S}{N_f} = 0.0323 \quad (3)$$

Following the computation of the $N_{PoS/CL}$ values (using Equation 2) for each required PoS/CL level, the S-N curve was fitted to the S-N data using the ESDU curve-fitting program, which is based upon maximum likelihood estimates [16]. The ESDU program identified the curve shape shown in Equation 4, where ‘ P_2 ’ is equivalent to ‘ σ_{FL} ’. To account for the statistically

reduced ‘ σ_{FL} ’ values, the appropriate σ_{FL} PoS/CL value was used for P_2 .

$$\sigma_a = P_1 N_{PoS/CL}^q + P_2 \quad (4)$$

In instances where $N_{PoS/CL}$ values fell below the resulting curve, the curve-fit was adjusted to enclose all

Table 2. Statistically reduced 4340 Steel S-N curves.

values of $N_{PoS/CL}$. The resulting PoS/CL curves are shown in Table 2. It is appreciated that a more statistically rigorous approach for producing the PoS/CL curves would be desirable, and this will be considered in Section 4. This section has shown that challenges exist when working with highly populated S-N datasets that contain run-outs.

PoS/CL	P1	q	P2 (σ_{FL}) MPa
50/50 Mean	15020	-0.4245	457.0
99/95	4523	-0.3281	421.6
97.7/95	5073	-0.3377	426.5
97.7/75	6206	-0.3516	429.3
95/75	6993	-0.3619	434.1

Figure 3 shows the PoS/CL curves and the S-N dataset for 4340 steel [15]. The S-N curves produced when applying the safety factors used in ASME III for nuclear components and Eurocode 3 for steel structures are also shown. Figure 3 shows that the S-N curves that

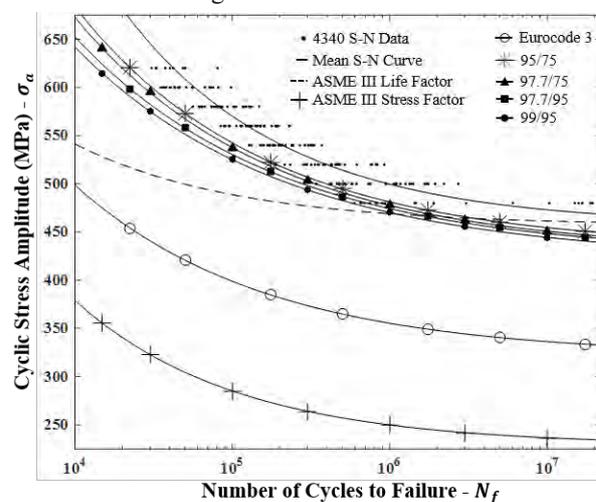


Figure 3. S-N curves from applying each conservatism approach to ESDU 4340 Steel S-N data

are based on safety factors produce significantly more conservative S-N curves than the statistically reduced PoS/CL curves. This could suggest that increased conservatism is introduced when using deterministic safety factors on S-N curves compared to statistically reduced curves.

Finally, it can be seen from the wide variety of PoS/CL curves (and their different impacts on the S-N curve shown in Figure 3) and safety factor values (shown by the numbers on Figure 2), that the magnitude of the conservatism applied is also inconsistent across the industrial sectors. As each industrial sector uses

different methods of applying conservatism, coupled with the fact that some sectors use multiple methods of applying conservatism to S-N fatigue analysis (e.g. using a PoS/CL S-N curve and a life-limit safety factor), it is not possible to directly compare the total magnitude of the conservatism introduced by each sector [3]. The reduction in a component life-limit (i.e. ‘impact’) could however, be used as a measure of the total magnitude of selected a conservatism approach. Therefore, a case-study can be used to quantify the impact on a component life-limit when using each of the industrial conservatism approaches. This is presented within the remainder of the paper.

This section has presented a comprehensive review of the conservatism approaches adopted across different industrial sectors. As has been discussed and shown in Figure 2, the approaches to conservatism are inconsistent across the different sectors. This inconsistency could lead to either under- or over-conservatism, as industrial sectors may not be appropriately accounting for the areas of variability and uncertainty present within the S-N fatigue analysis and design of life-limited components.

4 Case Study: Evaluating the Impact of Industrial Conservatism

In order to quantify the reduction of a component life-limit resulting from the different conservatism approaches, a case-study was developed. The case-study retained the component characteristics as defined within Sections 1.3.1 and 1.3.2: a single-load path, monolithic component manufactured from high-tensile steel and designed using a ‘life-limit’ and S-N approach. This section of the paper defines the case-study and presents the resulting life-limits of the component when applying the different conservatism approaches.

4.1 The SAE Keyhole Benchmark

A case-study familiar to the fatigue design community was selected in the form of the SAE keyhole benchmark shown in Figure 4 [17, 18]. Whilst the geometry of the benchmark has been unaltered, due to the richness of the ESDU S-N data [15], it was assumed that the case-study component was manufactured from 4340 steel. Various potential loading spectra are supplied with the SAE Keyhole benchmark and the ‘transmission’ spectrum (also shown in Figure 4) was selected due to the presence of tensile mean-stress, which would increase the number of damaging stress cycles extracted from the

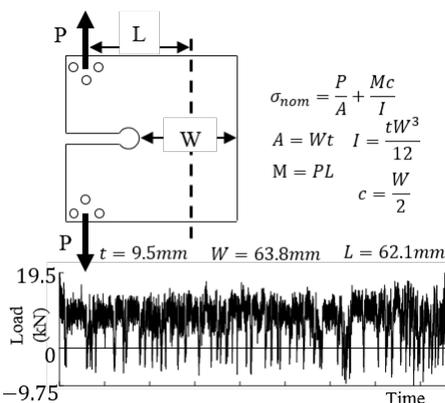


Figure 4. SAE Keyhole geometry, ‘transmission’ loading spectrum and stress analysis sourced from [18].

spectrum.

4.1.1 Computing the Component Life-Limit

The life-limit of the case-study component was computed using the S-N analysis process described in Section 1.3.2 for each conservatism approach shown in Figure 2. The conservatism was applied at the appropriate analysis stage, as shown in Figure 1. Where PoS/CL S-N curves were required, the appropriate curve equation from Table 2 replaced the mean S-N curve during analysis.

Following rainflow counting of the transmission loading spectrum, the cyclic loads were converted to cyclic stresses using the equations in Figure 4 [18]. These equations compute the nominal stress ‘ σ_{nom} ’ in the keyhole section. An elastic stress concentration factor of $K_T = 3$ was assumed to compute the stresses present at the keyhole as suggested in [18].

4.2 Impact of Conservatism Approach on Component Life-Limit

The case study component life-limits (e.g. the number of times that the ‘transmission’ load spectrum can be applied) resulting from each conservatism approach is shown in Table 3. The total accumulated damage from Miner’s Rule ‘ D_T ’ and the percentage reduction in the life-limit from the ‘baseline’ case (i.e. the mean S-N curve and no conservatism applied) is also shown.

Table 3. Life-limit reduction for the case-study component.

Sector	D_T	Life-Limit	% Reduction in Life-Limit
Baseline	3.02×10^{-5}	33157	-
Large Aircraft	1.02×10^{-4}	3273	90.13 %
Light Aircraft	2.41×10^{-4}	4144	87.50 %
Nuclear (Stress)	1.06×10^{-2}	94	99.72 %
Wind Turbines	2.47×10^{-3}	404	98.78 %
Offshore	7.00×10^{-4}	1428	95.69 %
Steel Structures	1.63×10^{-3}	615	98.15 %

4.2.1 Discussion

As can be seen from Table 3, the baseline component life-limit of 33157 cycles is significantly reduced following the application of the conservatism approaches, with a maximum life-limit of 4144 cycles for light aircraft structures, whilst the minimum life-limit was 94 cycles for nuclear components under the ASME III conservatism approach. Therefore, the conservatism approach that has the largest impact on the component life-limit is that used by the nuclear sector, reducing the life-limit by 99.7%. It is interesting to note that the conservatism impact for both large aircraft and light aircraft structures are similar in magnitude, producing a reduction in the component life-limit of 90.1% and 87.5% respectively. These results from the aerospace sectors contrast with the results from the remaining ‘land’ based sectors, which all show consistency in the percentage reduction in the life-limit. These range from 95.7% for offshore steel structures, 98.1% for Eurocode

3 steel structures, 98.8% for wind turbine components and 99.7% for nuclear components. This trend suggests that the conservatism approaches of the aerospace sectors introduce a smaller magnitude of conservatism (and hence impact on life-limit) compared to all other sectors. This may result from the requirement to minimise weight and the stringent characterisation of materials and loading data within aerospace design [19]. In addition, the aerospace sectors are the only sectors that require a full-scale test of the complete structure, whilst due to size and economic considerations in the other sectors, only full-scale testing of components (e.g. welded joints in the offshore sector) is performed [20]. As the full-scale test provides a “safety-net” for the fatigue analysis, this could also permit the aerospace sectors to introduce reduced conservatism. Previous work by Sutherland [21] also highlights that the different industrial sectors have different fatigue design cases. For example, wind turbine components have long target design lives (30+ years) and are exposed to many fatigue cycles due to the rotational nature of components (e.g. blade hubs) [21]. Offshore structures, with a 20-year target design life, are exposed to significant cyclic loading from wave and wind loads [11]. Nuclear components can have long design lives (40 years) and are also safety-critical [9]. The most severe fatigue design case would be a component that is highly cycled over a long target design life. On the other hand, aerospace structural components, whilst having typical design lives of 20 years [19] (which is lower than wind turbines, nuclear and steel structures) will also be exposed to lower level of cycling, due to the reduced rotational nature of components. These comparisons are shown in Figure 5, after [21]. Therefore, a trend exists between the more severe fatigue design cases (i.e. long design lives with highly cycled components) and the conservatism introduced by each sector. Super-imposed

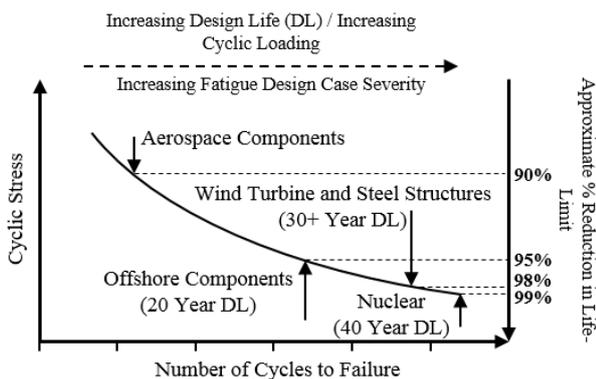


Figure 5. A comparison of the severity of the fatigue design case and percentage reduction of component life-limit for each industrial sector, modified from [21].

Table 4. Demonstration of how factors on stress can dramatically increase the percentage reduction in life-limit.

Sector	Factor on Stress	Number of Damaging Cycles Extracted	% Reduction in Life-Limit
Baseline	-	10	-
Large Aircraft	Statistically Reduced Fatigue Limit	21	90.13%
Nuclear	Stress Factor on S-N Curve	112	99.72%
Wind Turbines	Factor on Applied Stress, Statistically Reduced Fatigue Limit	66	98.78%
Offshore	Statistically Reduced Fatigue Limit	19	95.69%
Steel Structures	Statistically Reduced Fatigue Limit, Stress Factor on S-N Curve	57	98.15%

on Figure 5 are the percentage reductions in life-limit, showing that as the target design life or the cyclic nature of loading increases, the percentage reduction in the component life-limit also increases. It can therefore be suggested that sectors which anticipate more severe fatigue design cases introduce increased conservatism into S-N analysis. A final trend that the authors wish to explore in future work is the trend between the conservatism impact and the production volumes of each sector, which vary from potentially thousands in the aerospace sector to one-off components found in steel structures and the nuclear sector.

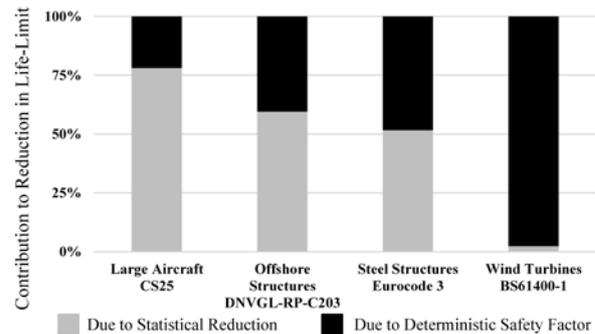


Figure 6. Breakdown of life-limit reduction into contribution from statistical reductions and safety factors.

4.3 Deterministic Safety Factors vs. Statistical Reduction Factors

As discussed in Section 3, a number of the industrial sectors reviewed use a mixture of both safety factors and statistical reduction factors within their conservatism approaches. Figure 6 shows the breakdown of the percentage reduction in the life-limit between the safety factors and statistical reduction factors.

Figure 6 shows that for large aircraft, offshore structures and steel structures, the majority of the life-limit reduction originates from the use of PoS/CL curves. Wind turbines on the other hand receive 97.7% of life-limit reduction from deterministic safety factors. This shows the significant impact that a safety factor applied to the cyclic stress magnitude can have. This is as a result of increasing the number of cyclic stress amplitudes that will lie above the fatigue limit. A similar effect is introduced by reducing the value of the fatigue limit, either through a deterministic stress safety factor on the S-N curve or through using PoS/CL S-N curves. This effect is shown in Table 4, whereby the different conservatism approaches are compared to the number of damaging cycles above σ_{FL} extracted by rainflow counting. Table 4 also shows the sensitivity of the reduction in component life-limit to the reduction in the

fatigue limit of the material.

Regarding safety factors and statistical reductions in general, statistical reductions are a more ‘flexible’ approach to applying conservatism than safety factors. This is because they are based upon the datasets of the specific design case, rather than the ‘general’ and deterministic nature of safety factors. It is interesting to note from Table 3 and Figure 2 that the two conservatism approaches that produced the minimum and maximum life-limit reductions (light aircraft and nuclear respectively) are both sectors that use only deterministic safety factors. This suggests that the introduction of conservatism through statistical reductions will be more representative of the specific design case at hand, potentially reducing the risk of producing an under- or over-conservative design. Therefore, the increased use of statistical reductions within fatigue design is suggested, to mitigate against un-safe or inefficient designs.

4.3.1 Identifying the Most Influential Area of Variability and Uncertainty.

From the split between the safety factors and statistical reductions shown in Figure 6, it can be seen that in most instances that when statistical reductions are applied, they account for at least 50% of the reduction in the component life-limit. Referring back to the matrix in Figure 2, it can be seen that statistical reductions are only applied to account for scatter within the S-N data. It can also be seen that when PoS/CL curves are used in conjunction with safety factors, that the safety factors are applied to account for various areas of variability and uncertainty. This shows that for most sectors, most of the conservatism applied accounts for scatter in S-N data. This suggests that the various industrial sectors consider scatter in S-N data to be the most influential area of variability and uncertainty within fatigue design. As Figure 6 suggests that S-N data scatter provides the largest contribution to the conservatism magnitude for each sector, increased statistical characterisation of S-N data could support a potential reduction in the conservatism currently required in the fatigue design of life-limited components.

5 Conclusions and Future Work

This paper has presented a comprehensive review and comparison of the conservatism approaches used during S-N fatigue design of life-limited components across a number of industrial sectors. A case-study, based upon the SAE keyhole benchmark has also been used to identify the impact on the component life-limit of each conservatism approach. The conclusions of this paper are:

- Conservatism approaches are inconsistent regarding the areas of variability and uncertainty accounted for, method of conservatism application and magnitude of conservatism.

- The conservatism approaches used by the large aircraft and light aircraft structures sectors result in a similar reduction in a component’s life-limit.
- A trend exists between the reduction in a component’s life-limit due to a sector’s conservatism approach and the severity of the fatigue design case for that sector.
- The conservatism approaches identify scatter in S-N data as the most influential area of variability.
- Increased use of statistical reduction factors and increased characterisation of the variability in S-N data could support a reduction in conservatism currently required in S-N fatigue analysis.

It should be noted that the findings of this paper are case-study specific and therefore, future work should apply further case-studies to observe whether the same conclusions can be drawn. In addition, future work should account for the variations in S-N fatigue analysis methods used within each industrial sector and should also use a more statistically rigorous approach to handling the variability in the fatigue limit and ‘run-outs’ in S-N data ([2] provides information on such an approach).

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