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Assessment of the Distribution of the Gaps Between Ring Flange Connections in Offshore Wind Turbines

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Abstract

Ring flange connections are commonly used to connect the tower of offshore wind turbines with monopile foundations. Studs in these ring flange connections are sensitive to fatigue damage accumulation, which is aggravated by gaps between the flanges. Such gaps are inevitable because of imperfections (out-of-flatness) of the flanges. Given the sensitivity of the forces in the studs with respect to the gaps, this study investigates the gaps of ring flange connections and proposes a method to assess the gap height and angle. To this end, the joint distributions of the gap heights and angles are determined for different tower diameters and production tolerances using manufacturing data. The type and parameters of the marginal distributions of the gap heights and angles are determined using the Maximum Likelihood Estimation method. Data censoring is applied to ensure that the tails of the gap height and gap angle distributions are accurately captured. Then, using the censored data and corresponding marginal distributions, the copula of the joint distribution is determined. The results show that the data is best represented by Weibull and Beta distributions for the gap height and angle, and the dependence structure is best described with Clayton copulas.

Keywords

Ring Flange Connections, Imperfections, Joint Distribution, Uncertainty Quantification

1 Introduction

The support structures of Offshore Wind Turbines (OWTs) are often connected using ring flange connections [1]. These ring flange connections exist of flanges welded to the tower and monopile shells that are connected with a series of preloaded bolts or studs. In the following study we refer to studs, as these are more common in modern connections. Since the support structures of OWTs are subjected to cyclic loading throughout their service life, and studs have a significant notch effect, fatigue failure of the studs in ring flange connections is an important failure mode to consider in the design of OWTs [2].

The loads on the studs in the ring flange connections are determined as a function of the loads acting on the tower, called the load transfer function, as visualized in Figure 1. Geometric imperfections of the ring flanges can cause gaps between the flanges and these significantly influence the load transfer function [3].

To account for these imperfections, the standard on wind turbine tower and foundation design IEC 61400-6 [4] provides imperfection tolerance limits. The limits are supposed to result in a safe design if used in combination with the Schmidt/Neuper load transfer function [5, 6]. However, Lüddecke et al. [1] have shown that this is not necessarily the case. Additionally, in recent years, the wind energy sector has been innovating rapidly and developing higher capacity OWTs that require larger support structures. The tolerance limits provided in IEC 61400-6 do not scale with the size of the ring flanges, making it difficult and expensive to comply with these limits for large ring flange connections.

To account for the rapidly changing industry, a different design philosophy is required. Rather than manufacturing the ring flanges to strict standards, which is a complex and expensive procedure, the ring flange connections should be designed considering the presence of imperfections.

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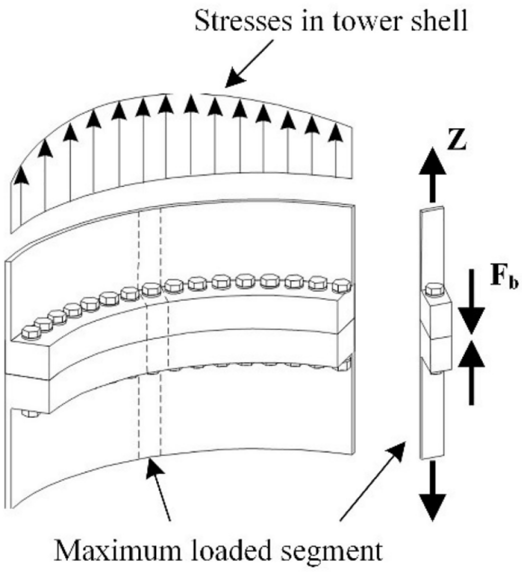

Figure 1 Diagram illustrating the shell forces Z inside the tower shell and the segment model with the bolt tension F_B, modified from [8].

This design philosophy is applied by Wegener [7], who determined the bolt loads in an imperfect ring flange connection using the finite element method, and Seidel [8], who proposed a load transfer function that accounts for the presence of imperfections.

To quantify the frequency and height of gaps, Buchholz and Seidel [9] created and studied a database of flatness measurements of manufactured ring flange surfaces. They developed a methodology to determine the contact points between two imperfect ring flanges, from which follows the length and height of the gaps between the contact points, as illustrated in Figure 2. The first contact point is found by the smallest distance between the top and bottom flanges. The top flanges are rotated around their horizontal axes until the flanges make contact on two additional positions other than the initial contact point, and the gap height is determined around the circumference based on the distance between the flanges.

This resulted in a database of matings that were classified as stable, bistable, and unstable contact conditions. A stable contact condition is defined as a condition in which the angles between all gaps are smaller than 180 degrees, which means that the top flange rests on the bottom flange and the tower cannot turn over under its self-weight. A bi-stable contact condition has a largest gap with an angle of 180 degrees, so that the tower can turn over to either side. In these cases, the third contact point was found by rotating over the plane between the two initial contacts until the third contact point was found. This procedure was performed for both rotation angles, resulting in two possible stable matings. An unstable contact condition has a largest gap larger than 180 degrees, meaning that the tower is likely to turn over due to self-weight. Buchholz and Seidel discarded these cases from their analysis. Subsequently, they determined the maximum heights of all the gaps in all combinations of flanges. They found that the height of the gaps can be described by a log-normal distributions, of which the parameters can be estimated as:

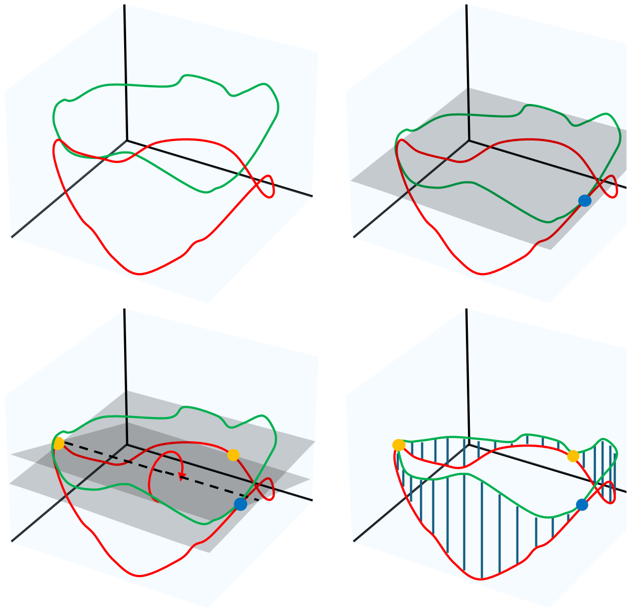

Figure 2 Example of two mated flatness measurements: a) Separated flanges, b) Initial contact point, c) additional contact points and resulting deflection, and d) stable mated condition, modified from [9].

$$E_{gap} \approx 0.01 l_k^2 + 0.2 l_k \quad (1)$$

$$V_{gap} \approx l_k^{-1.8} + 0.4 \quad (2)$$

where E_{gap} is the mean of the gap height in millimetres, V_{gap} is the coefficient of variation and l_k is the length of the gap in meters.

The Analysis of Flange Tolerance Relaxation and Shimming on Large-Diameter Bolted Connections (AFToR) project [10–12], as explained in [13], extended the study of Buchholz and Seidel with a larger database of flange matings and a refined methodology named the Additional Contact Point Analysis (ACPA) method. The methodology is changed to include the effects of additional contact points caused by the closure of gaps due to the self-weight of the tower and the application of low preload on the studs in the ring flange. Low preload is defined as 5 to 10% of the design preload. Based on the results of the AFToR project, Equation 1 and 2 are modified to account for the diameter of the ring flange and the production tolerances:

$$E_{gap} = \left(\frac{6.5}{D}\right)\left(\frac{u_{tol,1m}}{1.4}\right)(0.025 L_k^2 + 0.12 L_k) \quad (3)$$

$$V_{gap} = 0.35 + 200 \alpha_{gap}^{1.6} \quad (4)$$

where D is the diameter of the ring flange connection in meters, $u_{tol,1m}$ is the local flatness tolerance of a flange in millimetres per meter, and α_{gap} is the circumferential angle of the gap in degrees.

Considering that imperfections are known to have a significant influence on the fatigue loads of the stud, it is extremely important to quantify the size of the gaps. If the size of the gap is underestimated, it can lead to a significant reduction in the life of the studs and OWTs. Alternatively, if the size of the gap is overestimated, it can lead to very conservative ring flange designs. Prior studies consider the gap height distribution as a function of the gap

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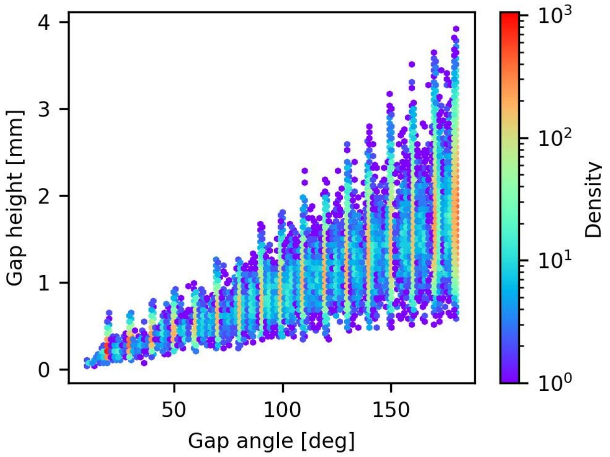

Figure 3 Gap height and gap angles for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m.

angle, but do not consider the distribution of the gap angle. Thus, this study aims to modify the uncertainty of the height and angle of the gaps between the flanges using a dataset of flange matings in such a way that the results can be used in the reliability analysis with respect to fatigue of studs in ring flange connections. First the correlation between gap height and gap angle is quantified. Then, the marginal distributions of the gap height and gap angle are fitted. The modelling of the tail of the gap height distributions is emphasized to ensure that the distributions are valid in the region of interest for reliability analysis. Finally, copulas are used to construct the joint distributions of the gap height and gap angle. Afterwards the conditional distributions of the gap height given the gap angle is investigated for different types of copulas.

2 Evaluation of flange mating data

2.1 Gap selection

A database of flange matings, using data from multiple manufacturers and wind parks, has been provided to the authors. The ring flange connections have been produced with an imperfection tolerance of 1.4 mm/m. The imperfections of the ring flanges have been measured after production, and the flange matings have been determined using these measurements. The dataset of flange matings provides matings based on 20 to 72 flatness measurements along the circumference of the ring flange. The gap heights and angles used in this study are obtained from the flange matings, using the methodology of Buchholz and Seidel [9].

The study only considers the gaps that are assumed to be the most critical gap of a mating, which are gaps with the highest height-to-length ratio, from now on referred to as the 'ratio' of each flange mating. Preliminary structural simulations with imperfect ring flanges modelled according to the guidelines described in [13] show that the fatigue performance of the studs depend on both the gap height and gap angle, and the ratio is a good indicator of the fatigue performance. Only considering the worst gap is standard practice in reliability analysis. However, it can be argued that this assumption is conservative since wind and wave loads are not omni-directional. Only a section of the ring flange experiences the design loads, thus it is conservative to assume that the worst gap always experiences the design loads.

Table 1 Kendall's τ for the investigated datasets.

Diameter [m] Imperfections [mm/m]	3 – 4m	4- 5m	6- 7m	7-8m
0.25 – 0.50	0.65	-	0.71	0.69
0.50 – 0.75	0.62	0.64	0.64	0.61
0.75 – 1.00	0.67	0.61	0.62	0.63

With the above-mentioned methodology, a database of 468907 gaps is created. These gaps are divided into four diameter groups ranging from 3 to 8 meters and four imperfection groups with measured imperfections ranging from 0.25-0.50 mm/m to 1.00-1.25 mm/m. Considering that the diameters of the flanges in the dataset are provided in bins, the circumferential gap length is normalized to gap angles in degrees.

2.2 Correlation between gap height and gap angles

The correlation between the gap height and gap angle is determined using the Kendall rank correlation coefficient, or Kendall's **τ**. Figure 3 shows a scatter plot of the heights and angles of the gaps, where the colour indicates the number of the observations. From visual observation of this figure, a positive correlation between the height and angle of the gaps follows. The Kendall's **τ** of the datasets are given in Table 1, and range between 0.61 and 0.71, confirming that there is consistent and moderate to high correlation between the angle and height of the gaps. Thus, the gap height and angle are best described using a joint distribution.

3 Joint distribution of the gap height and gap angle

The joint distribution of the gaps is determined using the inference for margins (IFM) approach [14] which allows the marginal distributions and copula to be determined independently. The marginal distributions and copula are quantified independently to reduce the model complexity and computational time.

3.1 Marginal distribution of the gap height

3.1.1 Maximum Likelihood Estimation

Based on a visual inspection of the data, it is assumed that the gap height is best parameterized by one of the extreme value distributions, namely the Gumbel, Fréchet, and Weibull distributions, which are widely used to model extreme events [15]. In addition to the extreme value distributions, the gap height data is evaluated for the log-normal distribution, as it is used in the literature to describe the distribution of the gap height.

The parameters of the marginal distributions of the gap

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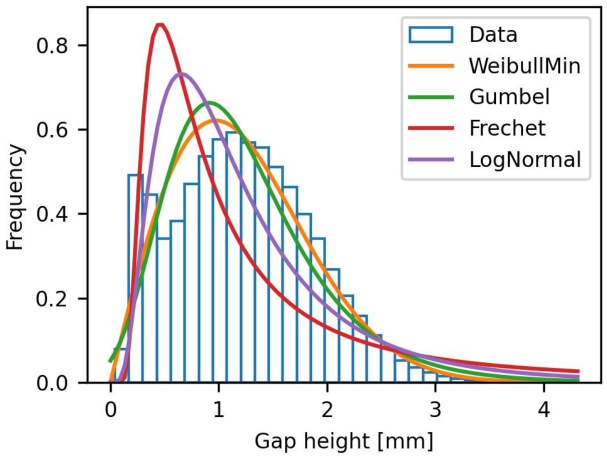

Figure 4 PDF of gap height for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m.

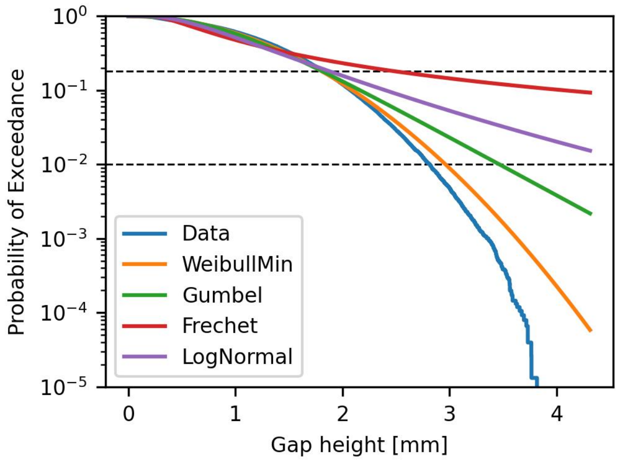

Figure 5 PoE functions of gap height for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m.

height are computed using the Maximum Likelihood Estimation (MLE) method. Considering that large gaps have a significant influence on fatigue life, the upper tail is the region of interest in this study. Left-hand censoring is applied to the dataset when necessary to ensure an accurate fit of the upper tail of the empirical distribution. Given a censoring threshold T, the likelihood of an observation exceeding the threshold is determined by the probability of the observation occurring, and the likelihood of an observation below the threshold is determined by the probability of the observation falling below the threshold. Thus, for a dataset containing n observations of which m do not exceed the chosen threshold T, the likelihood function used in the MLE is:

$$L(\theta) = [F_X(T|\theta)]^m \prod_{i=m+1}^{n} f_X(x_i|\theta) \tag{5}$$

where $L(\theta)$ is the likelihood of the observations x for the parameters θ, T is the censoring threshold, $f_X(x_i|\theta)$ is the Probability Density Function (PDF) and $F_X(T|\theta)$ is the Cumulative Density Function (CDF).

The differences between the likelihoods of the evaluated distributions are negligible, thus the distribution used in further analysis is picked based on a visual inspection of the data and the fitted distributions. Figure 4 shows the PDFs of the uncensored marginal distributions. To get a better impression of the tail of the dataset, Figure 5 shows the Probability of Exceedance (POE) of the dataset and the corresponding marginal distribution. The figures show that the Weibull distribution fits the gap heights best, but it still overestimates the tail of the distribution.

3.1.2 Threshold*Selection*

Left-hand censoring of the datasets ensures that the tail of the dataset is modelled accurately. But, this reduces the interval in which the distribution is representative of the data, and it leads to an increase of variability of the parameters as less data is included in the analysis. A parametric bootstrap methodology is used to determine the best censoring threshold, for which the distribution, as determined in Section 3.1.2., accurately describes the upper tail of the distribution [16]. To be more specific, we seek an accurate fit of the region of the upper tail that contributes to the failure probability of studs with respect to the fatigue limit state. We select the upper and lower bounds of the region of interest by resorting to the probabilistic definition of the design value given in design standards, which takes into account the target reliability level and the influence factors for dominant and non-dominant parameters.

The design value of variables can be determined using the design value format described in Annex C of EN 1990 [17]:

$$Y_d = F_Y^{-1}\big(\Phi(-\alpha_Y\beta)\big) \tag{8}$$

where Y_d is the design value of variable Y, F_y is the CDF of variable Y, Φ is the CDF of the Normal distribution, α_Y is the influence factor and β is the reliability index. Ring flange connections are a critical element in offshore wind turbines and have a maximum allowed annual failure probability of $5 * 10^{-4}$, which translates into an annual reliability index of β = 3.3 [13]. The influence factor can be broken down in the influence factors of the individual variables that constitute the resistance. A dominant variable has a higher influence factor than a non-dominant variable. As the influence factors are not known a priori, this paper considers the bounds for the influence factor of gap imperfection in agreement with recommendations in EN 1990: α_Y = -0.7 (for a dominant variable) as upper bound and α_Y=0.4 x -0.7 = -0.28 (for a non-dominant variable) as lower bound. This corresponds to exceedance probability values of 0.18 and 0.01 respectively, and are shown in Figure 5 with dashed lines. The best censor threshold is chosen by assessing the uncertainty of the estimated upper bound of the region of interest for each threshold value, using a parametric bootstrap method. First, for each candidate distribution and threshold, the parameters of the distribution function are determined with the MLE and the values of the upper bound of the region of interest of the gap height distribution is estimated. Then, from each distribution fitted, 1000 datasets with the same size of the initial database are generated. The procedure described in the prior step is repeated for each dataset, resulting in 1000 estimates of the upper bound of the region of interest for each threshold value. The 95% confidence intervals are computed from the 1000 estimates of these bounds. The best

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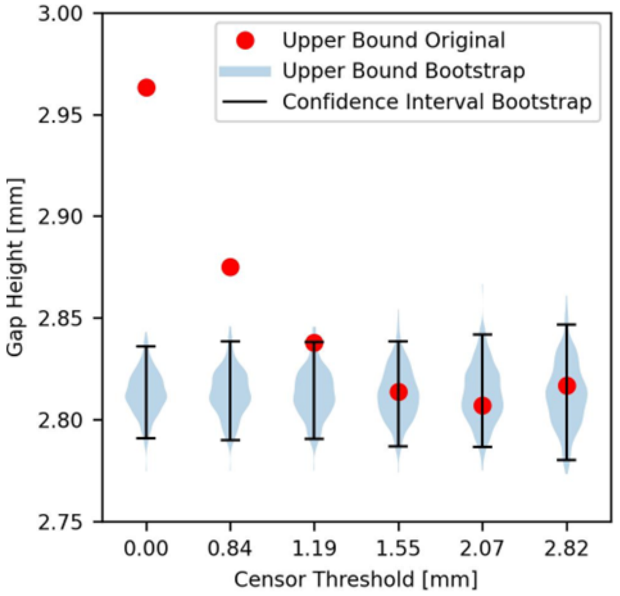

Figure 6 Upper bound values for of gap heights for gaps in the diameter group 7-8m with imperfections between 0.25-0.50mm/m using a 70% censored dataset.

threshold is chosen as the lowest threshold for which the upper bound of the region of interest determined in step 1 falls within the 95% confidence interval for all thresholds. With the same reasoning, the original distributions at that threshold level are rejected if one of the original design gap heights falls outside the confidence interval. In this case, the process is repeated for the distributions with the next-lowest threshold.

Figure 6 shows an example of the bootstrap. The bootstrap samples are based on the marginal distributions determined by MLE with the lowest 70% of the observations censored, which corresponds to gaps up to 1.19mm. The red dots are the values of the upper bound of the region of interest of the gap height determined by the distributions fitted over the original dataset, while the blue area shows the distribution of upper bound values of the gap height determined by the candidate distributions, and the black line shows the 95% confidence interval. When 70% of the data is censored, as shown in Figure 6, the upper bound values of the gap heights for all original

Table 2 Censor thresholds used in the datasets.

Diameter [m] Imperfections [mm/m]	3 – 4m	4- 5m	6- 7m	7-8m
0.25 – 0.50	50%	-	70%	70%
0.50 – 0.75	00%	50%	70%	70%
0.75 – 1.00	50%	90%	70%	50%
1.00- 1.25	50%	90%	-	-

marginal distributions with censoring thresholds above 70% fall within the confidence intervals, and therefore the marginal distributions determined with the 70% censoring threshold can be accepted. Distributions with a censoring threshold below 70% were tried but provided values outside the confidence interval.

Note that the differences between the upper bound values of the gap height with different censor thresholds are seemingly small, but the relation between the gap height and the fatigue life of studs is highly nonlinear, so this difference can have a significant influence on the calculation of the fatigue life of studs, thus a low variability is preferred.

3.2 Marginal distribution of the gap angle

Figure 7 provides the PDF of the gap angles for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m. The CDF of the data, as visualized in Figure 8, shows that there is a general trend which can be approximated by a continuous distribution. Since the gap angles are bounded to an interval between 0 and 180 degrees, the marginal distribution of the gap angle is fitted using a Beta distribution.

3.3 Copulas of the joint distribution

Copulas model the dependency between marginal distributions. Joint distributions with Independent copulas, i.e., no correlation, Gaussian copulas, Frank copulas, Clayton copulas and Gumbel copulas are evaluated.

Since the IFM approach allows the marginal distributions

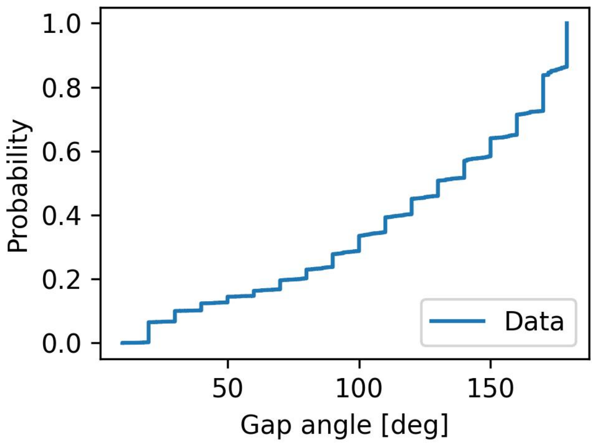

Figure 7 CDF of gap angles for gaps in diameter group 7- with imperfections between 0.25-0.50mm/m.

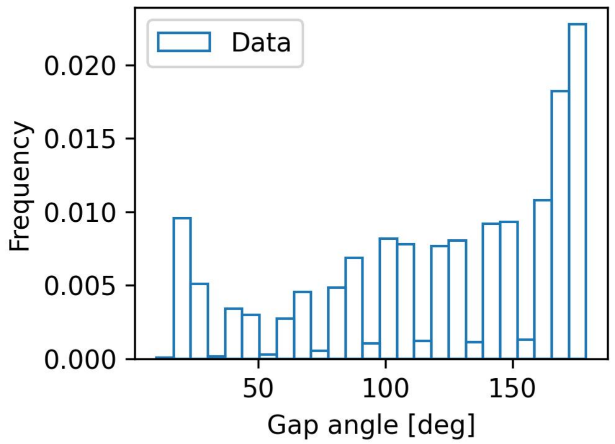

Figure 8 PDF of Gap angles for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m.

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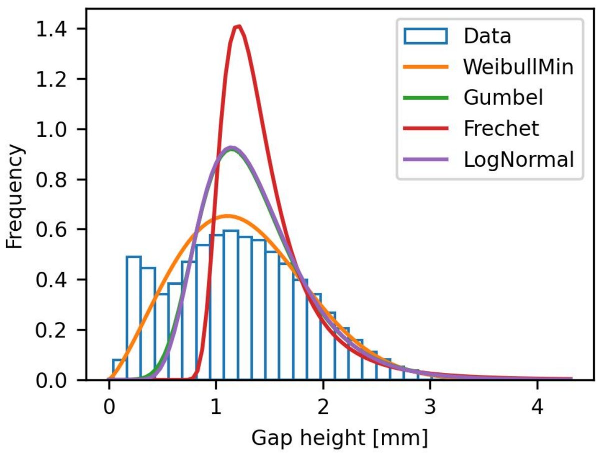

Figure 9 PDFs of the gap height for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m using a 70% censored dataset.

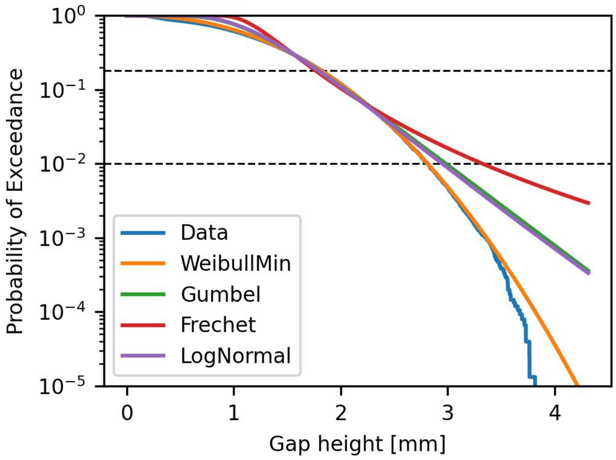

Figure 10 PoE's of the gap height for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m using a 70% censored dataset.

and copulas to be computed independently, the data censoring used for the marginal distribution of the gap heights is not necessary to include in the computation of the copulas. To find the best fitting of the copulas, the data is first transformed to the copula scale:

$$(u_{i1}, u_{i2}) := (F_1(x_{i1}), F_2(x_{i2})) \tag{11}$$

where (u_{i1}, u_{i2}) are the coordinates of observation i in copula-space, x_{i1} and x_{i2} are the observed gap height and gap length for observation i and F_1 and F_2 are the CDFs of the marginal distributions [18]. Since the gap heights and gap angles are positively correlated, it is not necessary to rotate the considered copulas. The likelihood is determined as:

$$L(\theta) = \prod_{i=1}^{n} c(u_{i1}, u_{i2}|\theta) \tag{12}$$

where $c(u_{i1}, u_{i2}|\theta)$ is the copula. Similar to the marginal distributions, the differences between the loglikelihood of the joint distribution with different copulas are negligible. The best fitting copula is selected through visual comparison of the gap height distributions, conditioned on both the mean and mode of gap angles, against the observed gap height data.

4 Results and discussion

4.1 Marginal distribution of the gap height

Since the differences between the posterior likelihoods of the Log-normal, Gumbel and Weibull distributions are small, the distributions are visually inspected to confirm the results. Figures 9 and 10 show the PDFs and PoE functions of the distributions and data for gaps in the diameter group 7-8m with imperfections between 0.25-0.50mm/m with a threshold of 70%, showing that the Weibull, Gumbel, and Log-normal distribution describe the data well. However, the Weibull distribution best represents the tail, the region of interest, and is therefore the distribution considered for further analysis.

Then the distributions which best represent the tail are selected using the parametric bootstrap method. Table 2 shows the censoring threshold for each dataset. In most cases the censor threshold is high with 70 or 90 percent of the dataset censored, from which it can be deducted that the gap heights do not conform to typical distributions. Although the cases with 90% censoring do not adhere to the initial requirements of the interval of the validity, the results are still valid in the interval $\alpha_Y = [0.38, 0.70]$ and useful for further analysises. The high censor thresholds means that the average gap height can be significantly under or over-estimated, as can be seen in Figure 9. However, the results are intended for reliability analysis, in which the tail of the distribution is important.

4.2 Marginal distribution of the gap angle

As discussed in Section 3.2 the gap angles are parameterized using the Beta distribution. As can be seen in Figure 11, the Beta distribution captures the trend of the gap distribution well, averaging out the stepwise increase of the gap angles. The Beta distributions tends to underestimate the presence of small gaps, which are gaps smaller than 60 degrees. While this is not ideal, it is expected to have little influence on the reliability analysis of ring flange connections.

4.3 Copulas

Figure 12 shows the PDF of the joint distribution of gap height and gap angles for gaps in in diameter group 7-8m

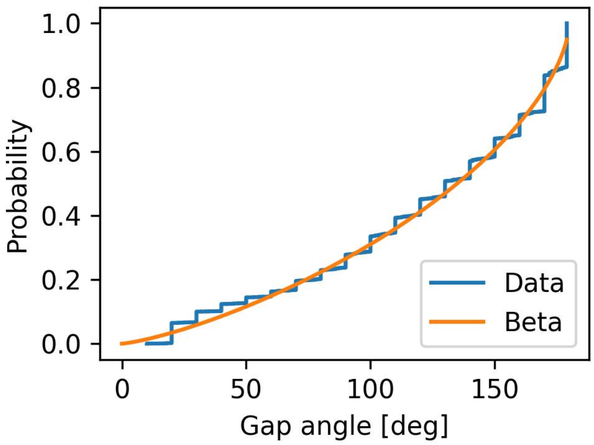

Figure 11 CDF of the beta distribution of the angles for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m.

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with imperfections between 0.25-0.50mm/m with a Clayton copula together with the original dataset. It can be seen that the contour of the PDF follows the dataset, but the height of minor gaps is overestimated. Figures 13 and 14 show the data and conditional distribution of gap heights for the mean and mode of the gap angles as an example, which are of respectively 126 and 180 degrees, for gaps in diameter group 7-8m with imperfections between 0.25-0.5mm/m. From the figures it can easily be deducted that a Clayton copula fits the data best even though the difference in the loglikelihood is small. The parameters of the marginal distributions and copulas of the joint distributions with a Clayton distribution are provided in Table 3.

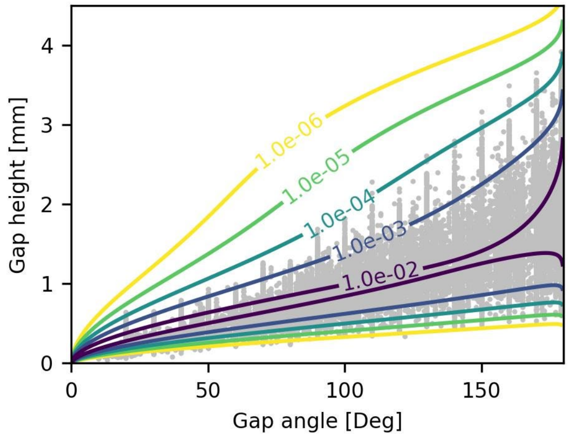

Figure 12 original data of the gap height and gap angles for gaps in diameter group 7-8m with imperfections between 0.25-0.50mm/m, and the PDF of the corresponding joint distribution.

5 Conclusion

This study provides a method to quantify and parametrize the gaps between ring flange connections. The study uses the APCA method [10-12] to create a gap database. The data is filtered such that only the 'worst gap' per mating is evaluated. It is shown that there exists a moderate to high correlation between the gap height and the gap angle.

Using the IFM approach, first the marginal distribution and then the gap heights have been determined. The differences between the loglikelihood of the different types of distributions is negligible, but it can visually be deducted that the gap height is best represented by the Weibull distribution. The parameters of the distribution have been estimated by MLE using left-hand censored datasets, resulting in distributions that accurately describe the region of interest of the distribution. The gap angles are fitted using Beta distributions, and though the distribution cannot represent the stepwise increase of the gap angle, it provides a good fit. Using the parameters of the gap height and gap angle distributions, the gap height and gap angle data are transformed using the CFDs and the copulas are determined. Similar to the marginal gap height distributions, there is no significant difference between the different types of copulas. By visually inspecting the fitted joint distribution, using conditional distributions, it is concluded that the Clayton copula result in the best fit. Gaps in the diameter group 6-7m with imperfections between 0.75-1.00mm/m are an exception and are best represented using a joint distribution with a Frank copula.

The resulting joint distribution can be used to determine the reliability of studs in ring flange connections with gaps between the flanges. It is emphasized that the distributions of the gap height are only valid in the interval described in Section 3.1.2. If the influence factor of the gap height is outside that interval, the data has to be re-evaluated to find the distributions that describe the region of interest.

There are several possible improvements for the proposed method. First, the study is performed on binned data, and the influence of the size of the bins is unknown. Repeating the study with a dataset with known flange diameters and imperfections might remove biases and provide more insight of the influence of the flange diameter on the gaps. Additionally, alternative copulas could be studied to improve the joint distribution. Next, the shape of the gaps could be studied, because it is expected to also influence the fatigue life of studs. Finally, as the gap height over gap angle ratio appears to be a strong indicator of the fatigue

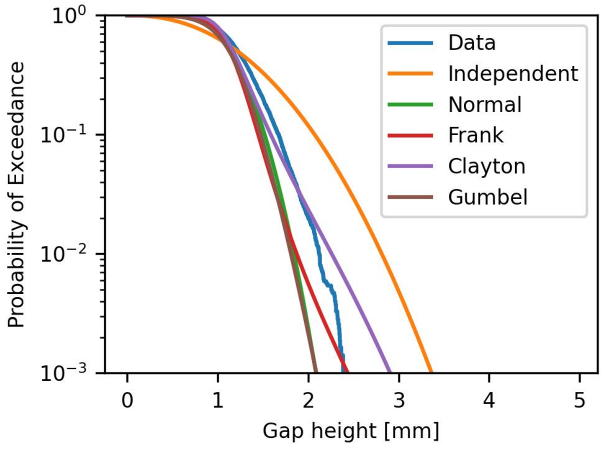

Figure 13 Original data and sampled data using a joint distribution with a Frank copula for gaps in in diameter group 7-8m with imperfections between 0.25-0.50mm/m for gap angles of 126 degrees.

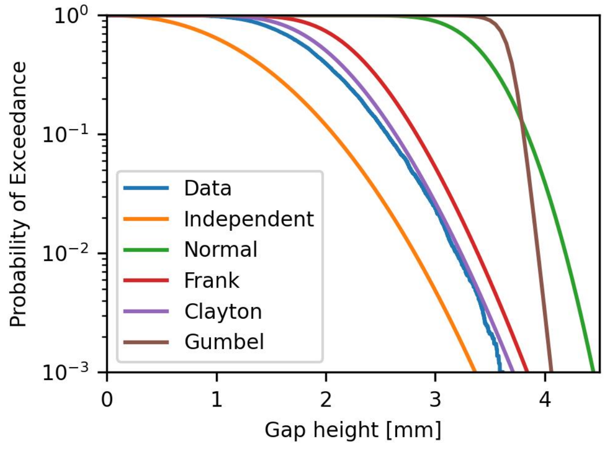

Figure 14 Original data and sampled data using a joint distribution with a Clayton copula for gaps in in diameter group 7-8m with imperfections between 0.25-0.50mm/m for gap angles of 180 degrees.

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performance of studs in a ring flange, the data could be censored on ratio rather than height, improving the joint distribution for small gaps.

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Table 3 Parameters of the marginal distributions and copulas.

Diameter [m]	Imperfections [mm/m]	Gap height Weibull distribution		Gap angle Beta distribution		Clayton Copula
		Scale factor β	Shape factor α	Shape factor α	Shape factor β	θ
3-4m	0.25 – 0.50	1.067	2.477	1.594	0.507	3.693
	0.50 – 0.75	1.465	2.544	1.717	0.570	3.228
	0.75 – 1.00	1.886	2.573	1.733	0.611	4.103
	1.00 - 1.25	2.730	2.682	1.975	0.482	3.517
4-5m	0.50 – 0.75	1.634	2.411	1.900	0.614	3.570
	0.75 – 1.00	2.276	2.461	1.929	0.542	3.113
	1.00 - 1.25	3.459	2.822	2.054	0.491	2.74
6-7m	0.25 – 0.50	1.269	2.319	1.422	0.626	4.873
	0.50 – 0.75	2.075	2.638	1.737	0.539	3.516
	0.75 – 1.00	2.543	2.718	1.469	0.5178	*8.583**
7-8m	0.25 – 0.50	1.433	2.264	1.289	0.608	4.558
	0.50 – 0.75	2.110	2.246	1.697	0.555	3.072
	0.75 – 1.00	2.698	2.374	1.429	0.499	3.396

* *Gaps in the diameter group 6-7m with imperfections between 0.75-1.00mm/m are the only dataset best represented using a Frank copula*

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