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A statistical approach to determine the seismic design parameters in the asymmetric sliding hinge joint using Belleville springs

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ABSTRACT

The design philosophy has changed over the past 20 years in seismic engineering. Structures moved from failing in a controlled ductile manner, to low damage design, to more recently, nearly no damage design (S. Ramhormozian, 2018). As low damage design is not an entirely brand-new concept, there has been designs around since the early 2000's. An example of this would be the asymmetric friction connection (AFC) proposed by Charles Clifton. This connection is used in moment resisting frames. The basic idea of the connection is a slotted bolted connection that allows movement during severe seismic events and dissipates the energy using friction. The current design has imperfections however, MVP interactions can cause bolt elongation and ply wear which mean the connection loses its clamping force. The solution proposed to fix these issues was developed and tested. Using asymmetric sliding hinge joints with partially deflected Belleville springs the bolt tension retaining and self-centring capabilities were greatly increased. The new design is in its final stages and requires data from test to be analysed to determine the seismic design parameters. This must be done using a statistical approach as to remove uncertainty from the final design values. The data achieved from two types of test rigs is analysed to find the appropriate distribution of the data and determine final values for different set-ups of the new design. After engaging both engineers and statistics expert a statistical process was applied. Using probability analysis and applying goodness of fit tests across the data provided it has been found that the stable sliding friction coefficient best matches a 3-parameter Weibull distribution. This approach has been found to increase certainty in the results and can be further applied to additional data in order to prepare the final design guideline for the asymmetric friction connection using Bellville springs.

1 INTRODUCTION

1.1 Design philosophy changes

Increasing population and economic growth has meant the construction industry has steady work ahead in all market sectors. In New Zealand, major cities are restricted by the amount of land available to grow outwards and needs to move forward into building upwards. This has been highlighted by proposed reforms to laws in the construction sector. Economic costs of earthquakes are high, not only in building repair and loss of rents/lease etc, but also if the damage is high enough, the complete demolition is the only option. The economic costs of damage have become such an issue as observed in the Christchurch earthquakes. Due to this, the low damage design philosophy has been adopted but this has evolved further to nearly no damage design in recent times (S. Ramhormozian, 2018). This philosophy is not only becoming popular with engineers but also owners and insurance companies ("Low-damage design," 2015). This gives a large economic motivation for research and development in this area as it is in the best interest of owners and their insurance companies. An example of this would be the asymmetric friction connection (AFC) proposed by Clifton (2005).

1.2 Current status of the AFC

A solution to fix the issues with the AFC was proposed by S. Ramhormozian, Clifton, MacRae, and Davet (2017). Using partially deflected Bellville springs (BeS), it has been shown that the bolts can maintain approximately 80% of the install tension after a seismic event (S. Ramhormozian, Clifton, Bergen, White, & Macrae, 2017). This is considered an acceptable range for nearly no damage design. It also improves the self-centring capabilities of the connection (S. Ramhormozian, Clifton, MacRae, Davet, & Khoo, 2019). The development of a theoretical bolt model and experimental testing for this upgraded connection have been undertaken (S. Ramhormozian, 2018). The connection has been tested in a similar manner as the current design where the design was put through one large seismic event followed by aftershocks. Then an additional set of tests was done that simulated two large seismic events, like the ones which were observed in the Christchurch earthquakes. The design is in its final stages where the experimental results need to be analysed to produce the final design values to use such as coefficient of friction and installed clamping force. This is to allow for the release of a design guideline for the new design configuration. The design parameters are required for engineers to use for designing new buildings with the connection and retrofit the currently used versions with the BeS. However, quantifying reasonable (i.e. not too high or not too low) seismic design parameters is essential. It is believed that using a robust statistical process, the current data can be analysed to derive the design values and remove variation to produce safe design guidelines.

1.3 Statistical analysis concept

Statistics is a branch of mathematics dealing with the collection, analysis, interpretation, and presentation of masses of numerical data (Merriam-Webster). It often deals with how data varies and can represent and explain changes in data. The three main methods can be; simple descriptive statistics e.g. mean, median etc, treating that data as a random variable, or trying to explain the variation in data by fitting a model that describes how the data varies relating to a set of variables. Often in seismic design the data of interest is assumed to be a random variable as a single factor is usually being analysed. This factor can be modelled by a probability distribution, for which there are many. This allows the entire data set to be mapped with only a sample of the set. This type of analysis is important observed phenomena rarely converges on a single point. The challenge comes in finding the correct distribution and extrapolating the correct information from it to apply to the wider engineering application. This is the focus for this research where in a process must be determined, validated, and then put into practice to derive the seismic design parameters for the new design.

2 BACKGROUND

A lot of work has been done on the AFC up until this point such as the works done by (Khoo et al., 2015) and (S. Ramhormozian et al., 2019). These have helped produce analytical models and experimental validation for both versions of the AFC i.e. with and without Belleville springs. The literature that best forms a background for what this research is trying to achieve are the papers that include statistical aspects to themsuch as (Wang & Pham, 2011). The purpose of this paper was to improve the method to find a sampling factor to divide the experimental factors in order to produce safe design values.

This paper mentions two statistical methods of obtaining design values from the test data.

1. Classical method (sampling factor is connected to confidence level), this is the most common method.
2. Bayesian method (sampling factor is based on the reliability index), this is more modern and is not commonly used by engineers today.

NZS1170.0 uses the classical method in the sampling factors and advice it provides for prototype testing. The current method applies the sampling factors based on using a minimum value. The paper suggests instead of using the minimum value it is better to use average values as there is less spread in the probability density function (PDFs). This can be shown in Figure 1 which is present in the report. The narrow curve of the Weibull probability distribution function of the mean does not have as large of a spread as compared to the minimum value. Further papers such as (Aslani & Miranda, 2005) and (Yazdani, Salehi, & Shahidzadeh, 2017) help further show the benefits of improved statistical analysis for results obtained during experiments in seismic engineering. The literature does not have specific focus on connection design and extraction of exact parameters to be used in the design with a robust statistical approach. This here forms the focus of the research

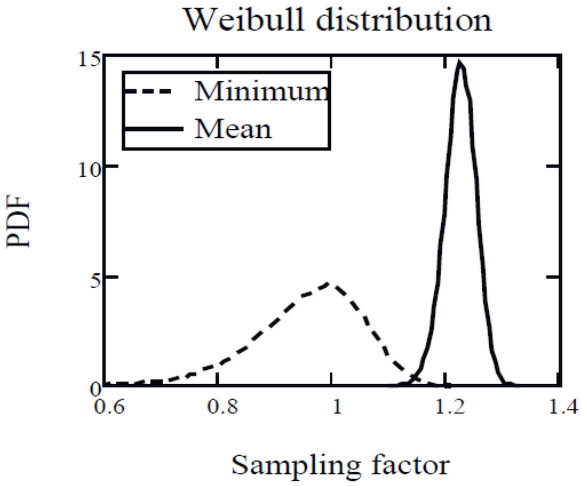


Figure 1: Example Weibull distributions for the average and minimum values

3 AIMS

- Use the experimental results presented in (S. Ramhormozian, 2018) to help determine the seismic design factors such as coefficient of friction.
- Determine a statistical approach that can be applied to this design and potentially others of similar nature in order to validate them.
- Determine appropriate clamping force values to use in design equations.

- Produce results to be used in the preparation of the simplified mathematical model and final design guideline to be provided to industry-based engineers.

4 METHODOLOGY

4.1 Test data and set-up

There have been two main experiments done on the AFC using Bellville springs which have been well summarized by (Bohl, 2019). The data extracted from these tests is what has been analysed. To help with determining the statistical procedure a statistic expert was engaged. This resulted in using probabilistic modelling in which the design values are treated as a random variable and matched to a probability distribution in order to make further predictions.

4.2 Extracting data

4.2.1 Coefficient of friction

This was done by extracting the entire curves data and placing it in a separate excel file. There were two cycles on each CoF vs displacement graph which were plotted in different colours to sperate them for further analysis. Two graphs were plotted to allow the top part of the curve (negative sliding direction) and the bottom part of the curve (positive sliding direction) to be brought up to a higher resolution. This enabled the correct identification of the points required for the stable sliding sections and hence the data to be used for the statistical analysis.

Each test had four sets of data to extract; first earthquake cycle in the positive sliding direction, first earthquake cycle in the negative sliding direction, second earthquake cycle in the positive sliding direction, and second earthquake cycle in the negative sliding direction. All the extracted data was put into a master excel file with a colour code to establish what cycle and sliding direction the data represented. The data was given a code based on the test, the cycle and the sliding direction. The code worked as follows:

- S1T1P1, S4T1N2
- The first part consisted of the spring amount: NS (no spring), S1, S2, S3, S4.
- The second part was the test number, in this case there was only one test analysed: T1.
- The final part represented the sliding direction and the cycle; P – positive sliding, N- negative sliding, 1 – first cycle, 2 – second cycle.

Only data from the first test rig was used for this research as there were larger sample sizes. This therefore resulted in a total of 20 sets of data. These came from tests with no springs, and 1 spring up to 4 springs (S1 to S4).

4.3 Initial approach

The initial idea was to use excel as the main software to develop a tool to match the probability distribution to the data. This tool was designed to simply copy and paste the data and the results would be presented to the user. This was designed to check the goodness of fit of the normal, Weibull and Lognormal distributions. The reason this approach was initially chosen was due to advice from engineering experts and from the probability distributions used in the literature. The tool was design so that the data could be copied and pasted into the excel spreadsheet and the outputs would be PDF and probability distribution functions (CDF) graphs along with a suitability check graph. However, after advice from a statistical expert this approach was abandoned for a more commercial piece of statistical software.

4.4 Matching a probability distribution

Minitab® was used for the final statistical analysis as it was the easiest to use and had the capabilities to process the data without a large amount of programming input. This enabled the data to be tested against the following probability distributions:

- Normal, Lognormal, 3-parameter lognormal, Exponential, 2-parameter exponential
- Weibull, 3-parameter Weibull, Smallest extreme value, Largest extreme value, Gamma, 3-parameter gamma, Loglogistic, 3-parameter loglogistic

The results from the analysis performed in Minitab® would give probability plots, and tables containing the Anderson-Darling goodness-of-fit statistic (AD), p-values, and likelihood-ratio test (LRT P) values. The AD stat tells the user how well a set of data fits a distribution, but it is only a comparative value which needs to be used in conjunction with other values. The p-value is a test whether a set of data could come from a specific distribution. If the p-value is larger than a given test value (0.05 for most cases) the user can be more certain that the data could come from a certain distribution. The LRT P value is used for distributions where a parameter has been added (i.e. going from a 2 parameter Weibull to a 3 parameter Weibull distribution) the larger the value the better effect the additional parameter has for matching the new parameterized distribution. The outputs would also check the suitability of a statistical transformation, but this information is to be ignored as this does not form part of the analysis.

Additional probability plots would be done once a distribution had been determined. This would help identifying the 5th and 95th percentile values which can be further assessed for the final design guideline. These would be the results of the statistical analysis and will be presented as a table of values. This probability-based approach will help better describe the friction value to prevent a building being too rigid or failing under less intense loading scenarios.

5 RESULTS

Analysing the statistical outputs as discussed above showed that the best fit for the data is a 3-parameter Weibull distribution.

$$f(x) = \frac{\beta}{\alpha^{\beta}}(x-\lambda)^{\beta-1}e^{\left[-\left(\frac{x-\lambda}{\alpha}\right)^{\beta}\right]} \qquad (1)$$

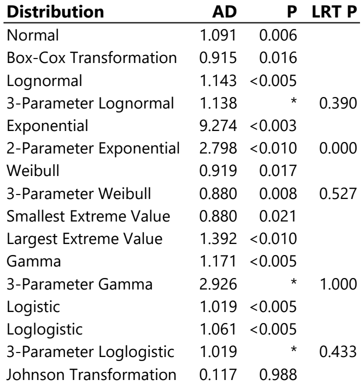
α = Scale Parameter

β = Shape Parameter

λ = Threshold Parameter

This can be seen in Table 1 and Figure 2

Table 1: Goodness of fit statistics produced by the Minitab® analysis



Distribution	AD	P	LRT P
Normal	1.091	0.006	
Box-Cox Transformation	0.915	0.016	
Lognormal	1.143	<0.005	
3-Parameter Lognormal	1.138	*	0.390
Exponential	9.274	<0.003	
2-Parameter Exponential	2.798	<0.010	0.000
Weibull	0.919	0.017	
3-Parameter Weibull	0.880	0.008	0.527
Smallest Extreme Value	0.880	0.021	
Largest Extreme Value	1.392	<0.010	
Gamma	1.171	<0.005	
3-Parameter Gamma	2.926	*	1.000
Logistic	1.019	<0.005	
Loglogistic	1.061	<0.005	
3-Parameter Loglogistic	1.019	*	0.433
Johnson Transformation	0.117	0.988	

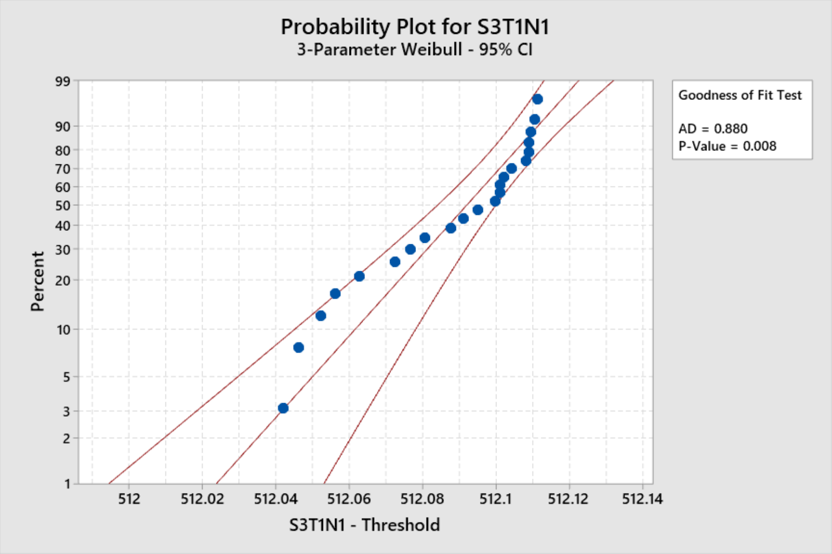


Figure 2:Probability plot for the 3-parameter Weibull distribution where the p value is less than 0.05

These outputs were generated for all data sets obtained from test rig 1 experiments. These were accompanied by PDF plots and out put tables with the PDF parameters, 5th and 95th percentile values.

6 DISCUSSION

6.1 Validity and Limitations of Statistical Method

The statistical analysis done on the test data from the first test rig gave good and relatively consistent results to be able to give confidence in the process. As shown by Yazdani et al 2017, expanding on what distributions used to analyse the data can be more accurate. In the process that has been followed, there has not been 100% consistency towards the distribution chosen to produce the results. There has been enough consistency however, to give confidence that the 3-parameter Weibull distribution is the best probability distribution to use to describe the data. Comparing what was originally proposed in the excel based method to what the final method has established, the latter has provided a greater statistical understanding and results. Engaging a statistics expert proved instrumental in getting the results. Using an experts who understands statistics in depth has enabled common practice and bias to be further removed from the process. This means a robust process for this connection has been developed and can enable the seismic design parameter to be extracted.

An interesting aspect that has been shown by the analysis is the small variation in the coefficient of friction where only one result had a 5th to 95th coefficient of friction ratio lower than 0.9. This is consistent with the underlying physics of this parameter as the coefficient of friction should be ideally and theoretically a fixed value for a given set of test conditions. There were some anomalies in the friction values for this first test which could be explained by the fact that this is a system coefficient of friction and other mechanism may be influencing this value (S. Ramhormozian et al., 2019).

The statistical process was determined that will be applied to additional test data for the final design guideline. The first test rig data is not the essential data needed for the final design guideline. This test was only used to give higher confidence in the distribution as there was more data available. Now that there is a good understanding of how the data behaves from a statistical perspective the second test rigs data set can be used with more confidence. This is an ongoing research being undertaken by the authors.

6.2 Wider Application of Statistical Method

Matching probability distributions is very common practice in a pure statistic discipline. In engineering however, the statistic knowledge is not at the forefront of the research. This has resulted in the same processes being applied with little review on them. It has been shown by expanding the statistical investigation that better results can be obtained for use towards design information. It is believed that this process will help the final development of the AFC and could be used in the development of similar designs.

6.3 Additional Work Required

There are still some final development steps involved in the preparation of the design guideline for the AFC using Bellville springs. Now that there is a robust statistical process, the second test rigs data can be used. This test rig can give us the practical results needed for the design guideline. The challenge with the data is that the sampling rates are low, and the hysteresis loops are not as well distinguishable to extract the data. This research provides more confidence in the results because the probability distribution is known. As this test focussed on the surface preparation and optimum bolt tension with all other factors fixed, there is a single factor can be studied. Once the statistical analysis has been applied to this, the design guideline can tell the engineer that for the shim type, with a certain surface preparation, there is a given reliable value of coefficient of friction. This is seen as a more appropriate way of providing engineers in industry with design guidelines as it improves design time efficiency.

7 CONCLUSION

The statistical processes applied can give more confidence in the data provided. Using goodness of fit tests has enabled a higher understanding on how data distributes itself. The 3-parameter Weibull distribution well described the data. The analysis showed that the stable sliding coefficient of friction did not vary extensively. Expanding the use of the probability distribution assessed to gain the best fit has improved accuracy which is not only shown in this research but other research as well. Consistently using the lognormal distribution may not be the most accurate practice going forward. Now that there is a good understanding of how the data behaves from a statistical perspective the second test rigs data set can be used with more confidence. This statistical process can be used to produce the design guideline. This guideline can tell the engineer that for the shim type, with a certain surface preparation, there is a given value of coefficient of friction. This improves the reliability of the design values and can reduce the amount of calculations and engineer in industry needs to do which improves design efficiency.

ACKNOWLEDGEMENT

Technical advice from Dr Victor Miranda (Auckland University of Technology) and Professor Timothy Sullivan and Mr Amir Orumiyehei (University of Canterbury), and supports from the Heavy Engineering Research Association (HERA) are much appreciated.

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